Perspectives on Nuclear Physics over the Past 100 Years

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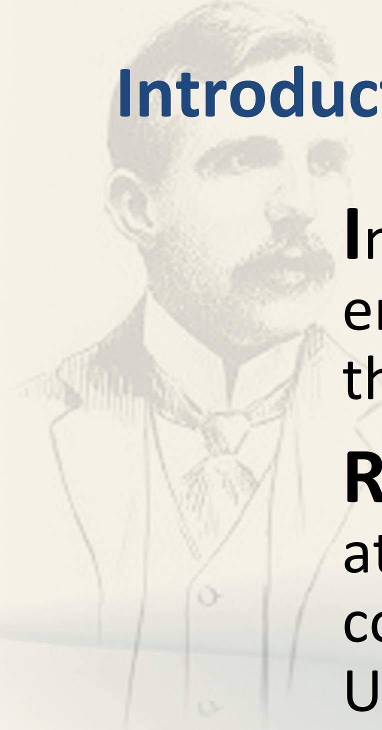


Introduction

In the 19th and 20th centuries humanity made enormous progress in understanding the way the physical world works.

Rutherford established that the core of the atom was a very dense chunk of matter that contained most of the mass of the visible Universe, but that required new rules of physics to be understood.

As a direct consequence of Rutherford's discovery, Niels Bohr developed Quantum Mechanics, defining the basic rules to guide physics through the next century.

Outline

The initial wave of discovery

Threads:

- **S**cattering to see what is inside.
- **S**tructure and symmetry.
- **A**pplications.
- **N**eutrinos.
- **O**rigin of elements, fuel of stars.
- **N**ew Forms of Matter.

Reflections

Conclusions

Initial Wave of Discovery
1912-1939

1913	*Bohr*	***Quantum mechanics*** and all that followed
1913	*Moseley*	X-ray sequence and charge of nuclei
1917	*Rutherford*	Nuclear ***transmutations***
1919	*Aston*	Discovery of ***isotopes***
1928	*Dirac*	Theory of the ***electron***
1930	*Pauli*	Suggestion of ***neutrino***
1932	*Chadwick*	Discovery of the ***neutron***
1932	*Anderson*	Discovery of the ***positron***
1934	*Yukawa*	Theory of ***nuclear force*** -- pion
1935	*Fermi*	Theory of ***beta decay***
1938	*Hahn & Meitner*	Discovery of ***fission***

1913: Quantum Mechanics

Bohr's first paper was based directly on Rutherford's work**.**

Phil. Mag. 26, 1 (1913)

From the Philosophical Magazine *for July* 1913.

On the Constitution of Atoms and Molecules.
By N. Bohr, *Dr. phil. Copenhagen* *.

Introduction.

IN order to explain the results of experiments on scattering of α rays by matter Prof. Rutherford † has given a theory of the structure of atoms. According to this theory, the atoms consist of a positively charged nucleus surrounded by a system of electrons kept together by attractive forces from the nucleus; the total negative charge of the electrons is equal to the positive charge of the nucleus. Further, the nucleus is assumed to be the seat of the essential part of the mass of the atom, and to have linear dimensions exceedingly small compared with the linear dimensions of the whole atom. The number of electrons in an atom is deduced to be approximately equal to half the atomic weight. Great interest is to be attributed to this atom-model; for, as Rutherford has shown, the assumption of the existence of nuclei, as those in question, seems to be necessary in order to account for the results of the experiments on large angle scattering of the α rays ‡.

* Communicated by Prof. E. Rutherford, F.R.S.
† E. Rutherford, Phil. Mag. xxi. p. 669 (1911).
‡ See also Geiger and Marsden, Phil.

1932: The Neutron

Chadwick discovers a new ‘elementary’ particle.

The Existence of a Neutron.

By J. Chadwick, F.R.S.

(Received May 10, 1932.)

§ 1. It was shown by Bothe and Becker* that some light elements when bombarded by α-particles of polonium emit radiations which appear to be of the γ-ray type. The element beryllium gave a particularly marked effect of this kind, and later observations by Bothe, by Mme. Curie-Joliot† and by Webster‡ showed that the radiation excited in beryllium possessed a penetrating power distinctly greater than that of any γ-radiation yet found from the radioactive elements. In Webster's experiments the intensity of the radiation was measured both by means of the Geiger-Müller tube counter and in a high pressure ionisation chamber. He found that the beryllium radiation had an absorption coefficient in lead of about $0{\cdot}22$ cm.$^{-1}$ as measured under his experimental conditions. Making the necessary corrections for these conditions, and using the results of Gray and Tarrant to estimate the contributions of scattering, photoelectric absorption, and ... in the absorption of such penetrating radi... radiation had a quantum energ... he found that the ... consist...

Proc. Roy. Soc. 136, 692-1932

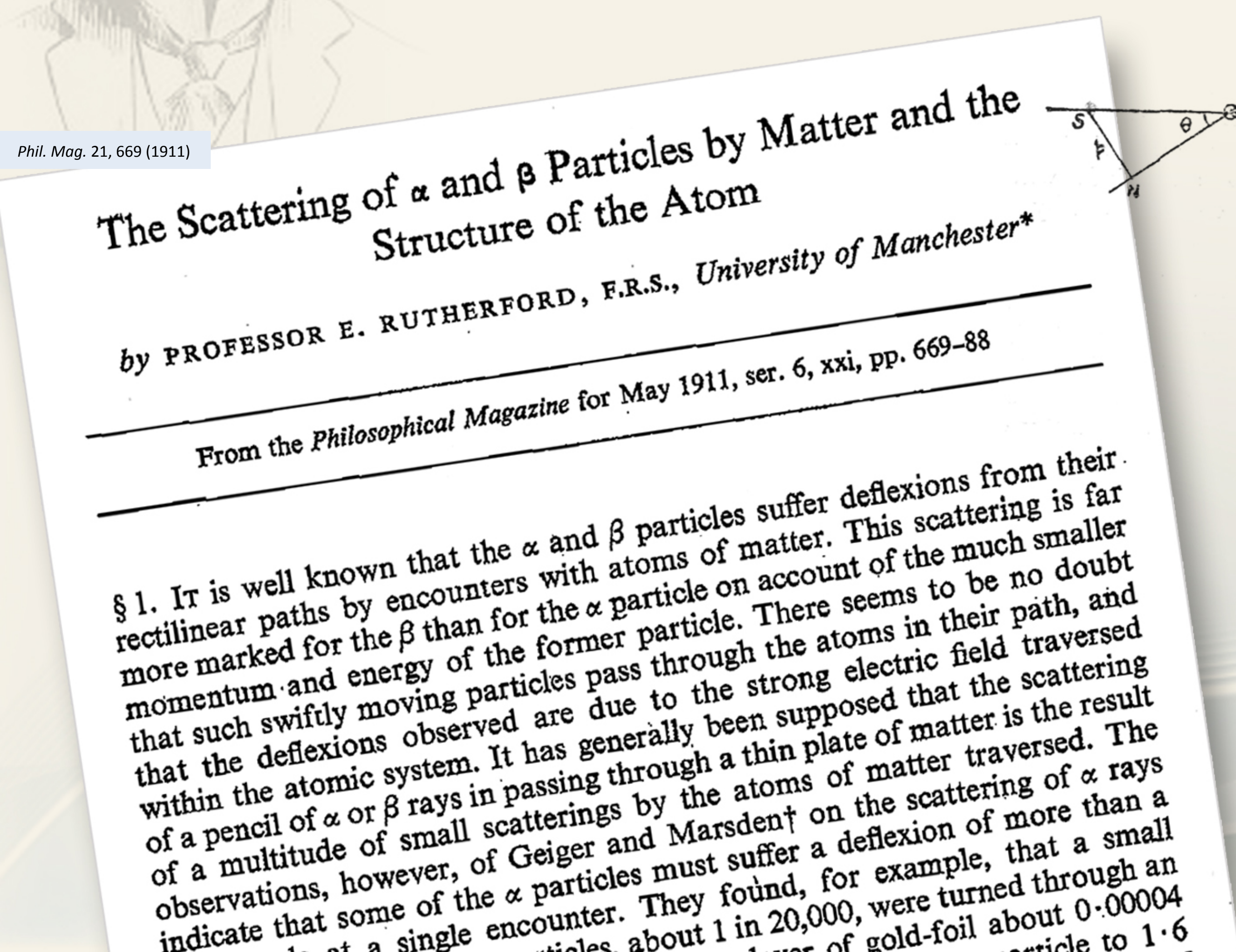
Thread:

Scattering to determine what’s inside

Scattering to determine what's inside

1911: The atom has a nucleus

Phil. Mag. 21, 669 (1911)

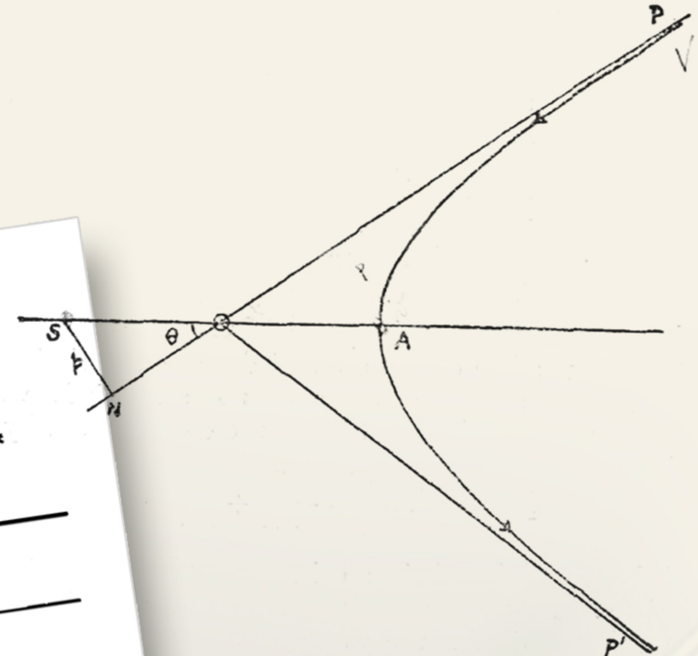


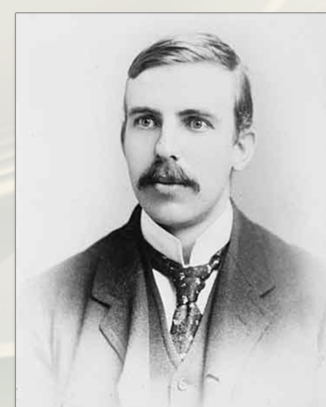
The Scattering of α and β Particles by Matter and the Structure of the Atom

by PROFESSOR E. RUTHERFORD, F.R.S., *University of Manchester**

From the *Philosophical Magazine* for May 1911, ser. 6, xxi, pp. 669–88

§ 1. It is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden† on the scattering of α rays indicate that some of the α particles must suffer a deflexion of more than a … at a single encounter. They found, for example, that a small … particles, about 1 in 20,000, were turned through an … of gold-foil about 0·00004 … to 1·6



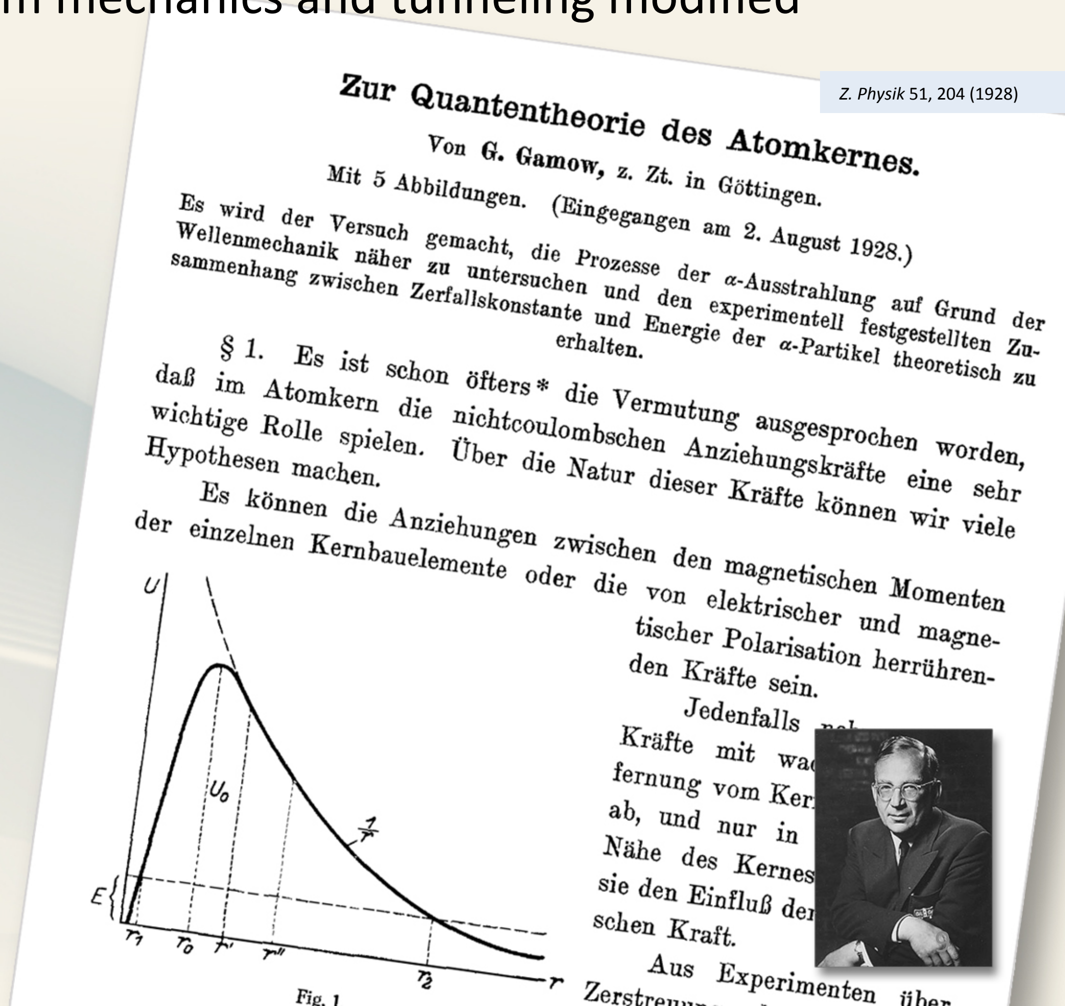


Estimates of nuclear size

Early estimates of nuclear radii came from: deviations in α-particle scattering, and also the onset of reactions.

Gamow's insight into quantum mechanics and tunneling modified classical arguments.

Z. Physik 51, 204 (1928)



Zur Quantentheorie des Atomkernes.

Von **G. Gamow**, z. Zt. in Göttingen.

Mit 5 Abbildungen. (Eingegangen am 2. August 1928.)

Es wird der Versuch gemacht, die Prozesse der α-Ausstrahlung auf Grund der Wellenmechanik näher zu untersuchen und den experimentell festgestellten Zusammenhang zwischen Zerfallskonstante und Energie der α-Partikel theoretisch zu erhalten.

§ 1. Es ist schon öfters* die Vermutung ausgesprochen worden, daß im Atomkern die nichtcoulombschen Anziehungskräfte eine sehr wichtige Rolle spielen. Über die Natur dieser Kräfte können wir viele Hypothesen machen.

Es können die Anziehungen zwischen den magnetischen Momenten der einzelnen Kernbauelemente oder die von elektrischer und magnetischer Polarisation herrührenden Kräfte sein.

Jedenfalls ... Kräfte mit wa... fernung vom Ker... ab, und nur in ... Nähe des Kernes ... sie den Einfluß der ... schen Kraft.

Aus Experimenten über Zerstreuu...

Fig. 1

Scattering to determine what's inside

Accelerators

~1928 request by Rutherford to get energetic projectiles to overcome the barrier.

Four, essentially simultaneous, ideas for accelerators.

Cyclotron *Lawrence*

Rhys. Rev. 38, 834. 1931

The Production of High Speed Protons Without the Use of High Voltages

A magnet having pole faces nine inches in diameter and producing a field of 15,000 gauss has recently been constructed and with its aid protons and hydrogen molecule ions having energies in excess of one half million volt-electrons have been produced.

ERNEST O. LAWRENCE
M. STANLEY LIVINGSTON

University of California,
July 20, 1931.

Cockroft-Walton

Proc. Roy. Soc. 137, 229) (1932)(

Experiments with High Velocity Positive Ions. II.—The Disintegration of Elements by High Velocity Protons.

By J. D. COCKCROFT, Ph.D., Fellow of St. John's College, Cambridge, and E. T. S. WALTON, Ph.D.

(Communicated by Lord Rutherford, O.M., F.R.S.—Received June 15, 1932.)

[PLATE 12.]

1. *Introduction.*

In a previous paper* we have described a method of producing high velocity positive ions having energies up to 700,000 electron volts. We first used this method to determine the range of high-speed protons in air and the results obtained will be described in a subsequent paper. communication we describe experiments which show that above 150,000 volts are capable of disintegrating ... have in the past ... particles ...

Phys. Rev. 43, 149 1933

THE PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics

VOL. 43, No. 3 — FEBRUARY 1, 1933 — SECOND SERIES

Van de Graaff

The Electrostatic Production of High Voltage for Nuclear Investigation

R. J. VAN DE GRAAFF,* K. T. COMPTON AND L. C. VAN ATTA, *Massachusetts Institute of Technology*

(Received December 20, 1932)

The developments in nuclear physics emphasize the need of a new technique adapted to deliver enormous energies in concentrated form in order to penetrate or disrupt atomic nuclei. This may be achieved by a generator of current at very high voltage. Economy, freedom from the inherent defects of an impulsive, alternating or rippling source and the logic of simplicity point to an ...

10,000,000 volts, and the fourth being an e... similar generator operating in a highly evacuat... Methods are described for depositing electric c... the belts either by external or by self-excitation. The upper limit to the attainable voltage is set by the breakdown strength of the insulating medium surrounding the sphere, and by its size. The upper limit to the current is ...

Arch. Elektrotech. 21, 387 (1928)

Linac *Wiederöe*

Über ein neues Prinzip zur Herstellung hoher Spannungen[1].

Von

Rolf Wideröe, Berlin.

I. Einleitung.
II. Die Bewegungsgleichungen des Elektrons.
III. Kinetische Spannungstransformation mit Potentialfeldern.
1. Das Prinzip.
2. Theorie der resultierenden Spannungen.
3. Die experimentelle Untersuchung.
4. Einzelheiten der Versuchsanordnung.
5. Aussichten des Verfahrens.
IV. Der Strahlentransformator.
1. Das Prinzip.
2. Die Grundgleichungen.
3. Experimentelle Untersuchungen.
V. Zusammenfassung.

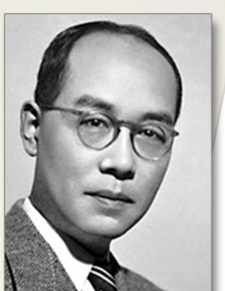
I. Einleitung.

To explain a small compact nucleus

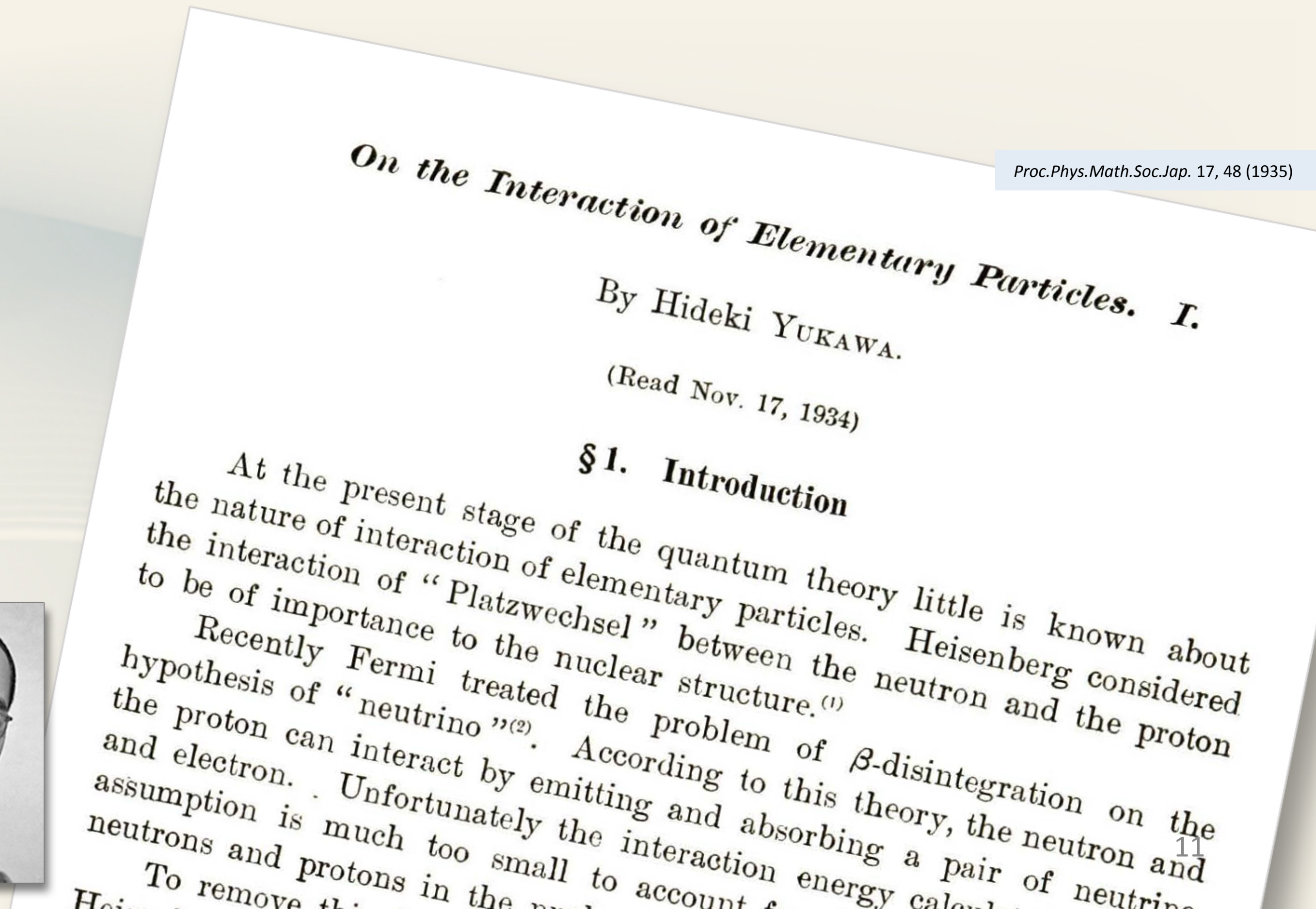
What is the origin of the short-range force?

Yukawa's 1934 insight (with the pion eventually discovered by Powell in 1947)

(*perhaps this is the start of 'high-energy physics' as a daughter of NP?*)



Proc.Phys.Math.Soc.Jap. 17, 48 (1935)



On the Interaction of Elementary Particles. I.

By Hideki YUKAWA.

(Read Nov. 17, 1934)

§1. Introduction

At the present stage of the quantum theory little is known about the nature of interaction of elementary particles. Heisenberg considered the interaction of "Platzwechsel" between the neutron and the proton to be of importance to the nuclear structure.(1)

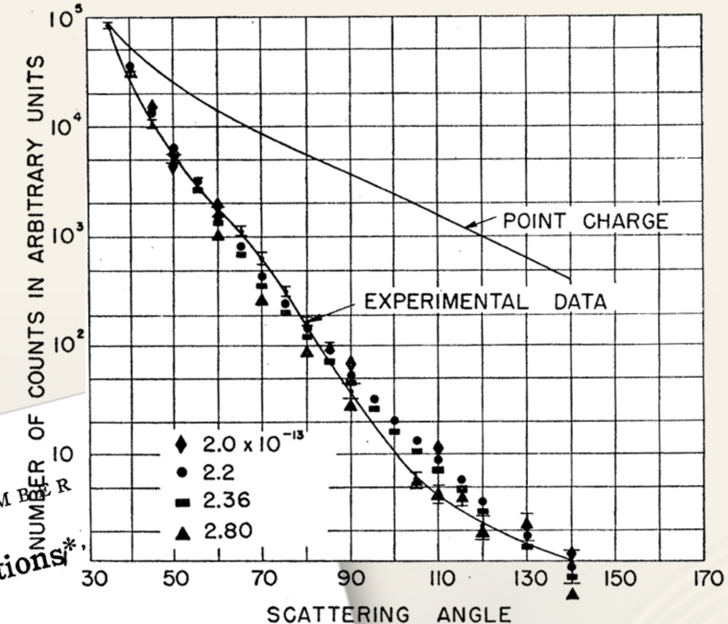
Recently Fermi treated the problem of β-disintegration on the hypothesis of "neutrino"(2). According to this theory, the neutron and the proton can interact by emitting and absorbing a pair of neutrino and electron. Unfortunately the interaction energy calcul… assumption is much too small to account f… neutrons and protons in the nucl…

To remove thi…

Scattering to determine what's inside

1953: Refined size and shape of nuclei and the nucleon

Electron scattering is a precise tool.



PHYSICAL REVIEW VOLUME 92, NUMBER 4 NOVEMBER

High-Energy Electron Scattering and Nuclear Structure Determinations*,

R. HOFSTADTER, H. R. FECHTER, AND J. A. MCINTYRE
Department of Physics and W. W. Hansen Laboratories, Stanford University, Stanford, California
(Received June 26, 1953)

Electrons of energies 125 and 150 Mev are deflected from the Stanford linear accelerator and brought to a focused spot of dimensions 3 mm×15 mm at a distance of 9 feet from a double magnet deflecting system. The focus is placed at the center of a brass-scattering chamber of diameter .20 inches. Thin foils are inserted in the chamber and elastically-scattered electrons from these foils pass through thin aluminum windows into the vacuum chamber of a double focusing analyzing magnet of the inhomogeneous field type. The energy resolution of the magnet has been about 1.5 percent in these experiments. This resolution is enough to separate clearly hydrogen or deuterium elastic peaks from carbon peaks in the same scattering target. The energy loss in the foils is readily measurable. In the case of light nuclei, e.g., H, D, Be, C, the shift of the peak of the elastic curve as a function of scattering angle indicates the recoil of the struck nucleus. Relative angular distributions are measured for Be, Ta, Au, and Pb. It is possible to interpret these data in terms of a variable charge density within the nucleus.

...DUCTION

...d that the ...

numerical error crept into Parzen's work and his published scattering curve cannot be considered reliable.[9] For nuclei having a uniform or spherical shell distribution of charge all Born approximation calculations predict ... and minima in the angular distribution ... essentially diffraction phenomena ... in electron diffrac- ... imation[2,4,7]

Phys. Rev. 92, 978 (1953)

1969: Substructure of the nucleon

Higher energy electron scattering yields direct evidence for quarks.

Phys. Rev. Lett. 23, 935 (1969)

VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

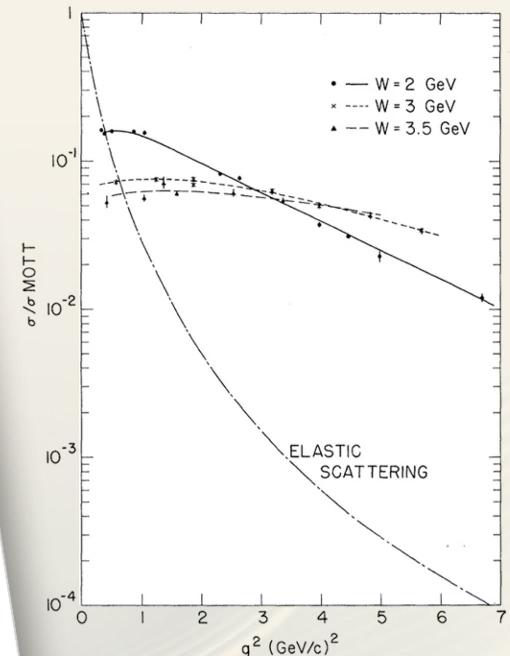
and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)

Results of electron-proton inelastic scattering at 6° and 10° are discussed, and values of the structure function W_2 are estimated. If the interaction is dominated by transverse virtual photons, νW_2 can be expressed as a function of $\omega = 2M\nu/q^2$ within experimental errors for $q^2 > 1$ (GeV/c)^2 and $\omega > 4$, where ν is the invariant energy transfer and q^2 is the invariant momentum transfer of the electron. Various theoretical models and sum rules are briefly discussed.

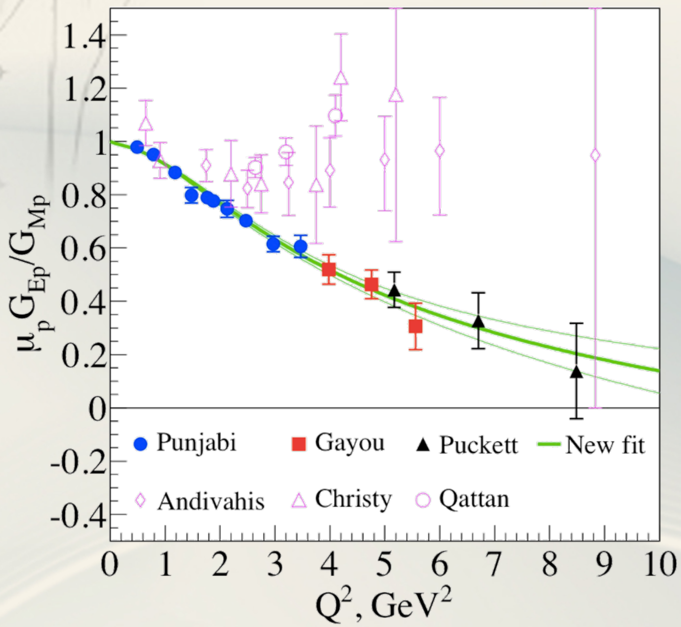
In a previous Letter,[1] we have reported experi-
...tal results from a Stanford Linear Accelera-
...husetts Institute of Technol-
...lectron-pro-

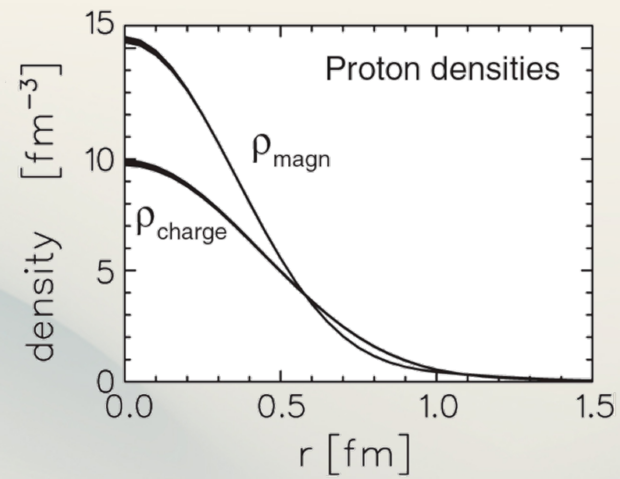
between the behavior of the inelastic and elastic cross sections is also illustrated in Fig. 1, where the elastic cross section, divided by the Mott cross section for $\theta = 10°$, is included. The q^2 dependence of the deep continuum is also consider-



2007: The nucleon has a different shape in charge density than in magnetization

Precision measurements with polarized electrons finally show this, and correct previous attempts based on longitudinal-transverse separation.





A. Puckett *et al*, arXiv:1102.5737

What gives mass to the proton and other hadrons?

Atoms and nuclei are lighter than their bound constituents.

Proton mass is ~2 orders of magnitude *heavie*r than that of the sum of its constituent quarks.

How and why are hadrons different?

Modern theoretical understanding of hadrons: *courtesy of Craig Roberts*

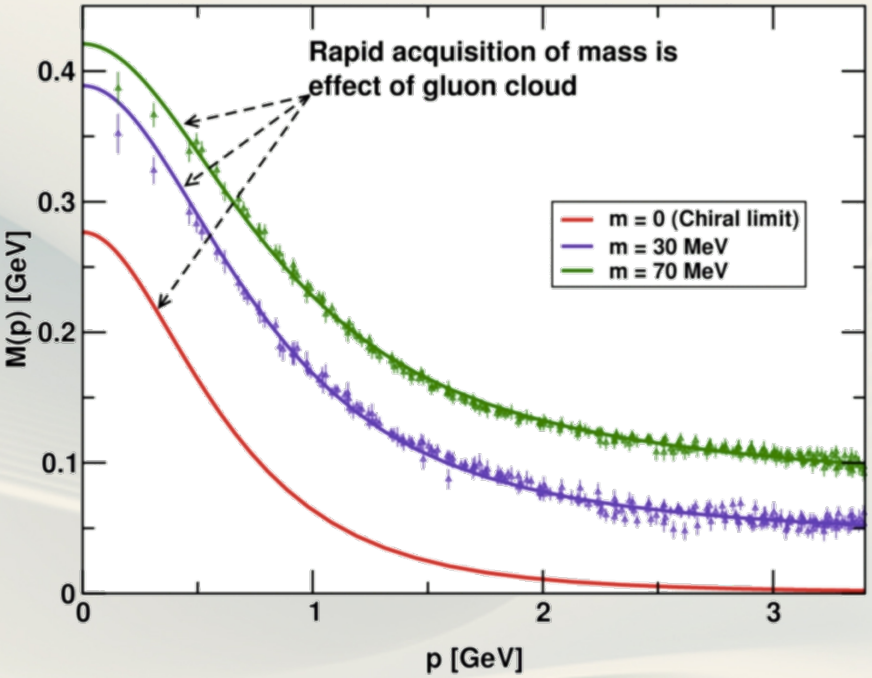
Quarks acquire dynamically generated momentum-dependent mass from chiral symmetry breaking predicted by Nambu.

Gluons also contribute at low momenta.

These *emergent* phenomena have an enormous impact:

they are responsible for 98% of the 'visible' mass .

It is widely conjectured that they share a common origin with confinement



Thread:

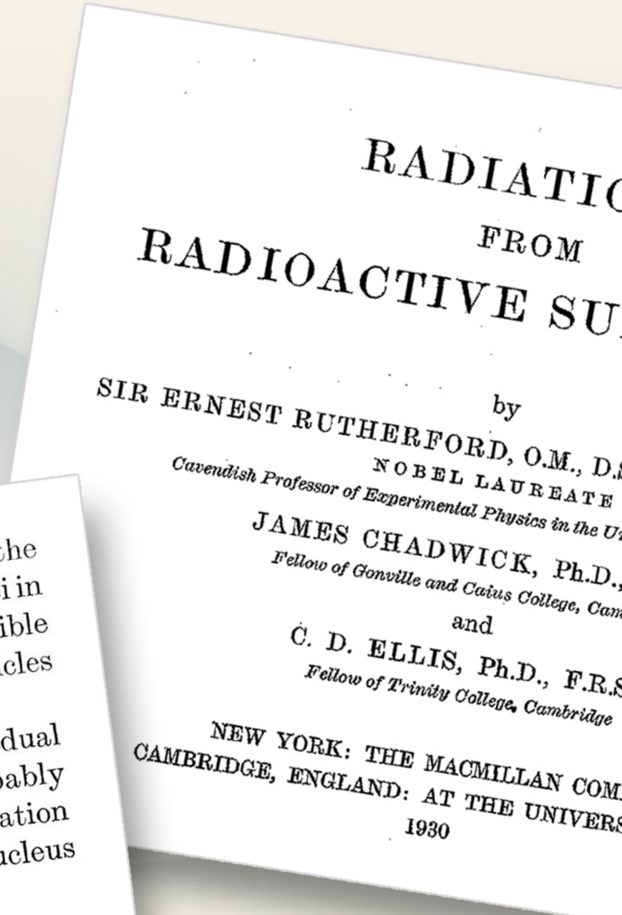
Structure and Symmetries

(of nuclei)

The first textbook on Nuclear Physics

Rutherford, Chadwick and Ellis (1930)

The nucleus is made of α-s, electrons and protons



RADIATIONS
FROM
RADIOACTIVE SUBSTANCES

by

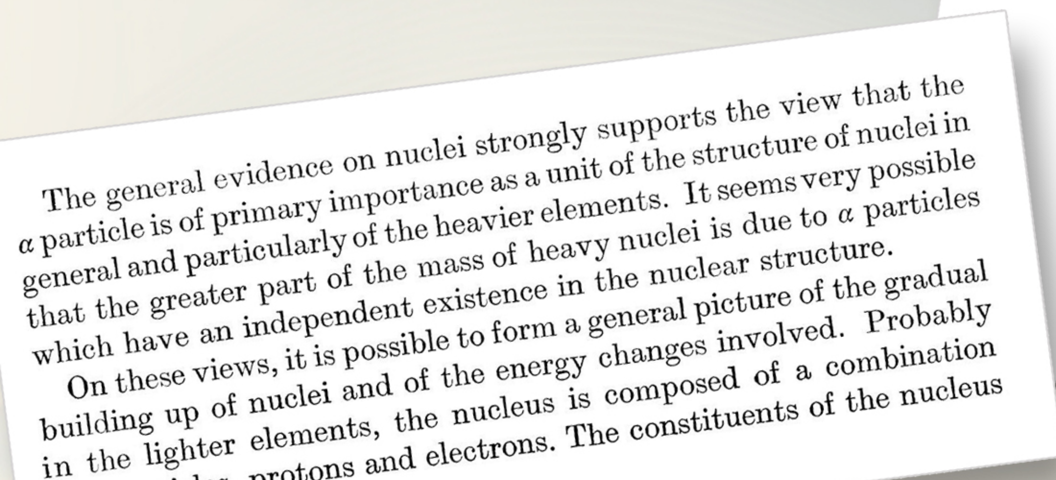
SIR ERNEST RUTHERFORD, O.M., D.Sc., Ph.D., LL.D., F.R.S.
NOBEL LAUREATE
Cavendish Professor of Experimental Physics in the University of Cambridge

JAMES CHADWICK, Ph.D., F.R.S.
Fellow of Gonville and Caius College, Cambridge

and

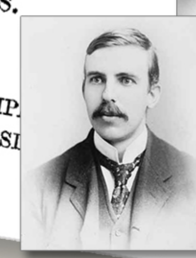
C. D. ELLIS, Ph.D., F.R.S.
Fellow of Trinity College, Cambridge

NEW YORK: THE MACMILLAN COMP
CAMBRIDGE, ENGLAND: AT THE UNIVERSI
1930



The general evidence on nuclei strongly supports the view that the α particle is of primary importance as a unit of the structure of nuclei in general and particularly of the heavier elements. It seems very possible that the greater part of the mass of heavy nuclei is due to α particles which have an independent existence in the nuclear structure.

On these views, it is possible to form a general picture of the gradual building up of nuclei and of the energy changes involved. Probably in the lighter elements, the nucleus is composed of a combination protons and electrons. The constituents of the nucleus



After the neutron is discovered

In the 1936 Review Article by Bethe and Bacher (the *Bethe Bible)* the thinking was summarized; topics discussed about nuclear structure are:

- The α-particles are subunits of heavier nuclei.
- Quantum States of Individual Particles (Neutron and Proton "Shells")
- Evidence for Periodicities from the Energies of Nuclei
- Periodicities in the Existing Isotopes.

The 'shells' seemed to work up to ^{40}Ca, but not beyond. Bethe and Bacher comment:

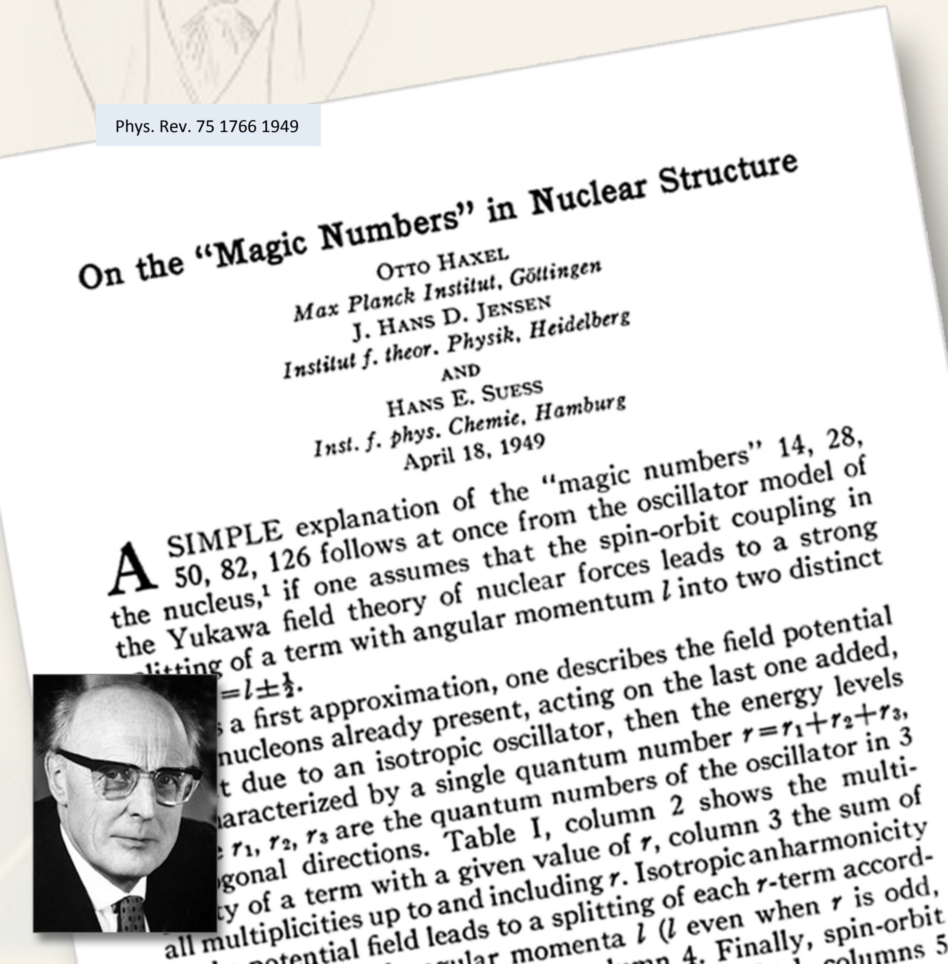
> ***"it is necessary to give a strong warning against taking the shells too literally … this has been done too frequently in the past with the effect of discrediting the whole concept of shells among physicists."***

1948: The *Shell Model* <u>*does*</u> work

A strong spin-orbit interaction accounts for the magic numbers.

The nucleus is amazingly transparent: an average potential, representing interactions with other nucleons, works remarkably well.

Phys. Rev. 75 1766 1949



On the "Magic Numbers" in Nuclear Structure

OTTO HAXEL
Max Planck Institut, Göttingen
J. HANS D. JENSEN
Institut f. theor. Physik, Heidelberg
AND
HANS E. SUESS
Inst. f. phys. Chemie, Hamburg
April 18, 1949

A SIMPLE explanation of the "magic numbers" 14, 28, 50, 82, 126 follows at once from the oscillator model of the nucleus,[1] if one assumes that the spin-orbit coupling in the Yukawa field theory of nuclear forces leads to a strong splitting of a term with angular momentum l into two distinct ... $=l\pm\frac{1}{2}$.

... a first approximation, one describes the field potential ... nucleons already present, acting on the last one added, ... t due to an isotropic oscillator, then the energy levels ... aracterized by a single quantum number $r=r_1+r_2+r_3$, ... r_1, r_2, r_3 are the quantum numbers of the oscillator in 3 ... gonal directions. Table I, column 2 shows the multi- ... ty of a term with a given value of r, column 3 the sum of all multiplicities up to and including r. Isotropic anharmonicity ... potential field leads to a splitting of each r-term according ... angular momenta l (l even when r is odd, ... column 4. Finally, spin-orbit ... columns 5

Phys. Rev. 44 235 (1948)

THE PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 74, NO. 3 AUGUST 1, 1948

On Closed Shells in Nuclei*

MARIA G. MAYER
Argonne National Laboratory and Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received April 16, 1948)

Experimental facts are summarized to show that nuclei with 20, 50, 82, or 126 neutrons or protons are particularly stable.

IT has been suggested in the past that special numbers of neutrons or protons in the nucleus form a particularly stable configuration.[1] The complete evidence for this has never been summarized, nor is it generally recognized how convincing this evidence is. That twenty neutrons or protons (Ca^{40}) form a closed shell is predicted ... the Hartree model. A number of calculations ... port this fact.[2] These considerations will not ... peated here. In this paper, the experimental ... indicating a particular stability of shells of ... 82 protons and of 50, 82, and 126 neutrons ... listed.

I. ISOTOPIC ABUNDANCES

... ussion in this section will be mostly ... the heavy elements, which for this ... be defined as ...

abundance of a single isotope is ... 60 percent. This becomes more ... increasing Z; for $Z>40$, relati... greater than 35 percent are no... The exceptions to this rule are giv... (b) The isotopic abundances ... metrically distributed around the c... light, neutron-poor isotopes have ... dances. The concentration of the lig... is, as a rule, less than 2 percent. Th... to this rule are listed in Table II. It is seen that the violations of ... regularities occur practically only at neutron numbers 50 and 82. Only the case of ... in Table II, which ... exceptio...

ISOSPIN: a simple symmetry that works!

Z. Physik 77, 1 (1932)

Über den Bau der Atomkerne. I.

Von **W. Heisenberg** in Leipzig.

Mit 1 Abbildung. (Eingegangen am 7. Juni 1932.)

...rden die Konsequenzen der Annahme diskutiert, daß die Atomkerne ...rotonen und Neutronen ohne Mitwirkung von Elektronen aufgebaut ... § 1. Die Hamiltonfunktion des Kerns. § 2. Das Verhältnis von Ladung ...Masse und die besondere Stabilität des He-Kerns. § 3 bis 5: Stabilität ...Kerne und radioaktive Zerfallsreihen. § 6. Diskussion der physikalischen Grundannahmen.

Durch die Versuche von Curie und Joliot[1]) und deren Interpretation ...rch Chadwick[2]) hat es sich herausgestellt, daß im Aufbau der Kerne ...n neuer fundamentaler Baustein, das Neutron, eine wichtige Rolle spielt. ...ieses Ergebnis legt die Annahme nahe, die Atomkerne seien aus Protonen ...nd Neutronen ohne Mitwirkung von Elektronen aufgebaut[3]). Ist diese Annahme richtig, so bedeutet sie eine außerordentliche Vereinfachung für die Theorie der Atomkerne. Die fundamentalen Schwierigkeiten, denen man

1932: Heisenberg suggests to treat neutrons and protons as states of the same particle. But Wigner points out that the Coulomb energies are comparable to nuclear ones and will likely destroy the symmetry.

Phys. Rev. Lett. 7, 250 (1961)

EVIDENCE FOR CHARGE INDEPENDENCE IN MEDIUM WEIGHT NUCLEI*

J. D. Anderson and C. Wong

Lawrence Radiation Laboratory, University of California, Livermore, California

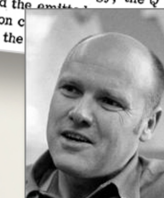
(Received July 26, 1961)

The importance of isotopic spin considerations ($\Delta T = 0$) in "mirror nuclei" (p,n) reactions has been pointed out by Bloom et al.[1] If one goes to nonmirror nuclei such as V^{51}, Cr^{51}, the (p,n) reaction is assumed to go as follows: The incoming proton reacts with an $f_{7/2}$ neutron, exchanges its charge, and is emitted as a neutron. In the initial state there are eight $f_{7/2}$ neutrons available and three $f_{7/2}$ protons. Since, by definition of isotopic spin state (charge independence), all the nuclear interactions within the initial and final nucleus are the same, the Q for the (p,n) reaction between V^{51} $(T=\frac{5}{2})$ and its analog state in Cr^{51} is the Coulomb energy difference. It is the purpose of this Letter to point out that direct-reaction neutrons from the (p,n) reaction on medium weight nuclei do indeed leave the residual nucleus in a state which is the analog of the ground state of the bombarded nucleus.

Neutron spectra at $\theta_L = 23°$ have been measured for proton energies between 9 and 13 Mev using a self-supporting 8-mg/cm² vanadium foil and a 10-meter flight path. The neutron spectra for three incident proton energies are shown plotted in Fig. 1. The compound statistical model predicts that if a sufficient number of nuclear levels are involved in both the compound nucleus and the residual nucleus, the energy distribution of neutrons emitted is given by

$$P(E)dE = KE\omega(E_{\mathrm{excit}})\sigma_c(E)dE,$$

where $\omega(E_{\mathrm{excit}})$ is the level density of the residual nucleus at its excitation energy, which is determined by the incident proton energy, the Q value of the reaction, and the emitt... ergy; $\sigma_c(E)$ is the reaction c... inverse reaction between the...



1963: The symmetry is found to work well, even in the heaviest nuclei. The long range of the Coulomb force helps preserve the symmetry. (one of the rare cases where Wigner was wrong!)

Nature, 172, 576 (1953)

ISOTOPIC SPIN SELECTION RULES

By Dr. D. H. WILKINSON

Cavendish Laboratory, Cambridge

Isotopic Spin

...ng been recognized that, in some sense or ...the neutron and proton may be regarded as ...e states of the same particle, distinguished, ...any specific assumption about nuclear forces, ...value of the isotopic spin co-ordinate[1]. The ...value of the individual nucleon, the projection ...spin of the z-axis is represented by the value of ...h on the z-axis is represented by a strong formal ...topic spin co-ordinate, bears a strong formal ...lance to ordinary intrinsic spin; the isotopic spin operators are closely related to the Pauli spin matrices. The idea of alternative nucleon states is ... by the near-identity of the masses of

~1950: As data accumulate in light nuclei, the isospin symmetry seems to work remarkably well.

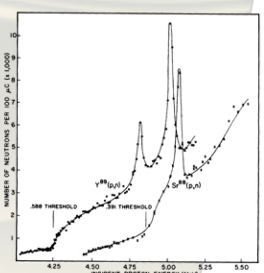
Phys. Rev. Lett. 12, 198 (1964)

EXCITATION OF ISOBARIC ANALOG STATES IN ^{89}Y AND ^{90}Zr†

J. D. Fox, C. F. Moore, and D. Robson

Department of Physics, Florida State University, Tallahassee, Florida

(Received 16 October 1963; revised manuscript received 17 January 1964)



We wish to report the excitation of compound nucleus resonances in ^{89}Y and ^{90}Zr by proton bombardment of ^{88}Sr and ^{89}Y, respectively. These states are interpreted as isobaric analogs of the corresponding low-lying states of ^{89}Sr and ^{90}Y. Thin evaporated targets of natural strontium (83 % ^{88}Sr) and yttrium (100 % ^{89}Y) on evaporated carbon backings were bombarded with protons and the resulting neutrons detected with a Hanson-McKibben long counter placed at 50° to the beam direction and at 65 cm from the target. The same targets were also used for measurements of (p,p) elastic-scattering ... butions using juncti... chamb...

1948: Nuclei exhibit collective 'Giant Resonance' degrees of freedom

Phys. Rev. 74, 1046 (1948)

PHYSICAL REVIEW

VOLUME 74, NUMBER 9 NOVEMBER 1, 1948

On Nuclear Dipole Vibrations

M. GOLDHABER
Department of Physics, University of Illinois, Urbana, Illinois

AND

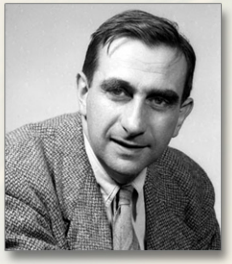
E. TELLER
Institute of Nuclear Studies, University of Chicago, Chicago, Illinois

(Received July 22, 1948)

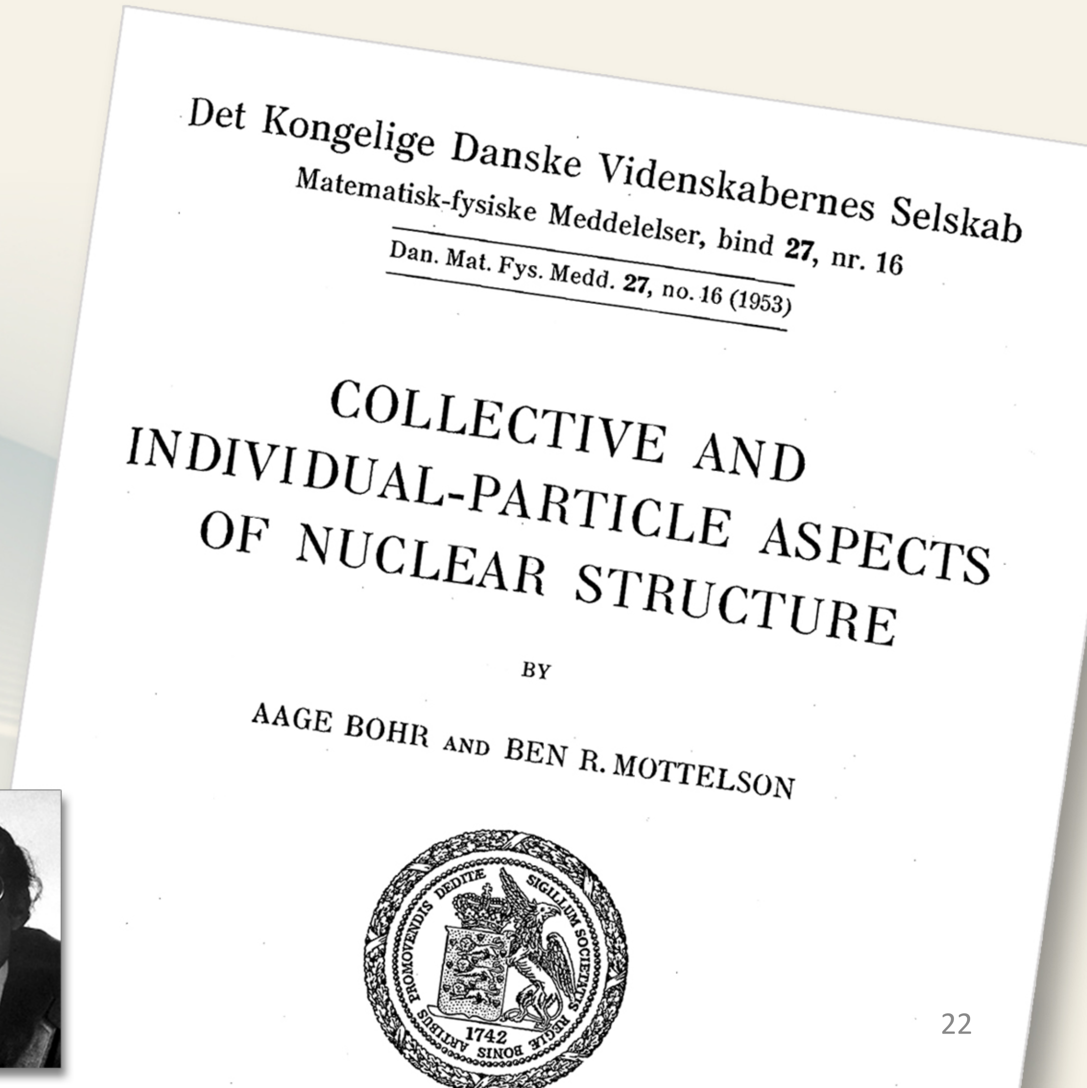
The high frequency resonances recently observed for (γ,n) reactions as well as photo-fission are interpreted in analogy with the "reststrahl frequencies" of polar crystals. The estimated frequencies are in good agreement with the experimental results. An interesting consequence of this interpretation is the conclusion that strong resonance scattering of γ-rays should take place at a frequency characteristic of the scattering nucleus.

IT has been observed recently[1] that some nuclear photo-disintegrations, (γ,n) reactions as well as photo-fission, exhibit a behavior which has the appearance of a high frequency resonance. Such a resonance was observed in carbon at 30 Mev,[1] in copper at 22 Mev,[1] in tantalum at 16 Mev,[2] and for photofission in thorium and in uranium at 16–18 Mev.[1] The suggestion was made that this phenomenon ...

"dipole vibration." Such a vibration will have a high frequency as a result of the partial separation of the protons from the neutrons to which they are strongly bound. The maximum in the γ-absorption cross section will give rise to similar maxima for several nuclear processes ...




1953: Nuclei have static deformations, and exhibit rotational and vibrational bands



Det Kongelige Danske Videnskabernes Selskab

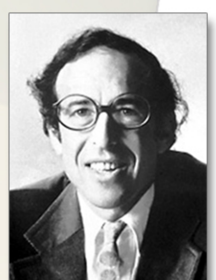
Matematisk-fysiske Meddelelser, bind **27**, nr. 16

Dan. Mat. Fys. Medd. **27**, no. 16 (1953)

COLLECTIVE AND INDIVIDUAL-PARTICLE ASPECTS OF NUCLEAR STRUCTURE

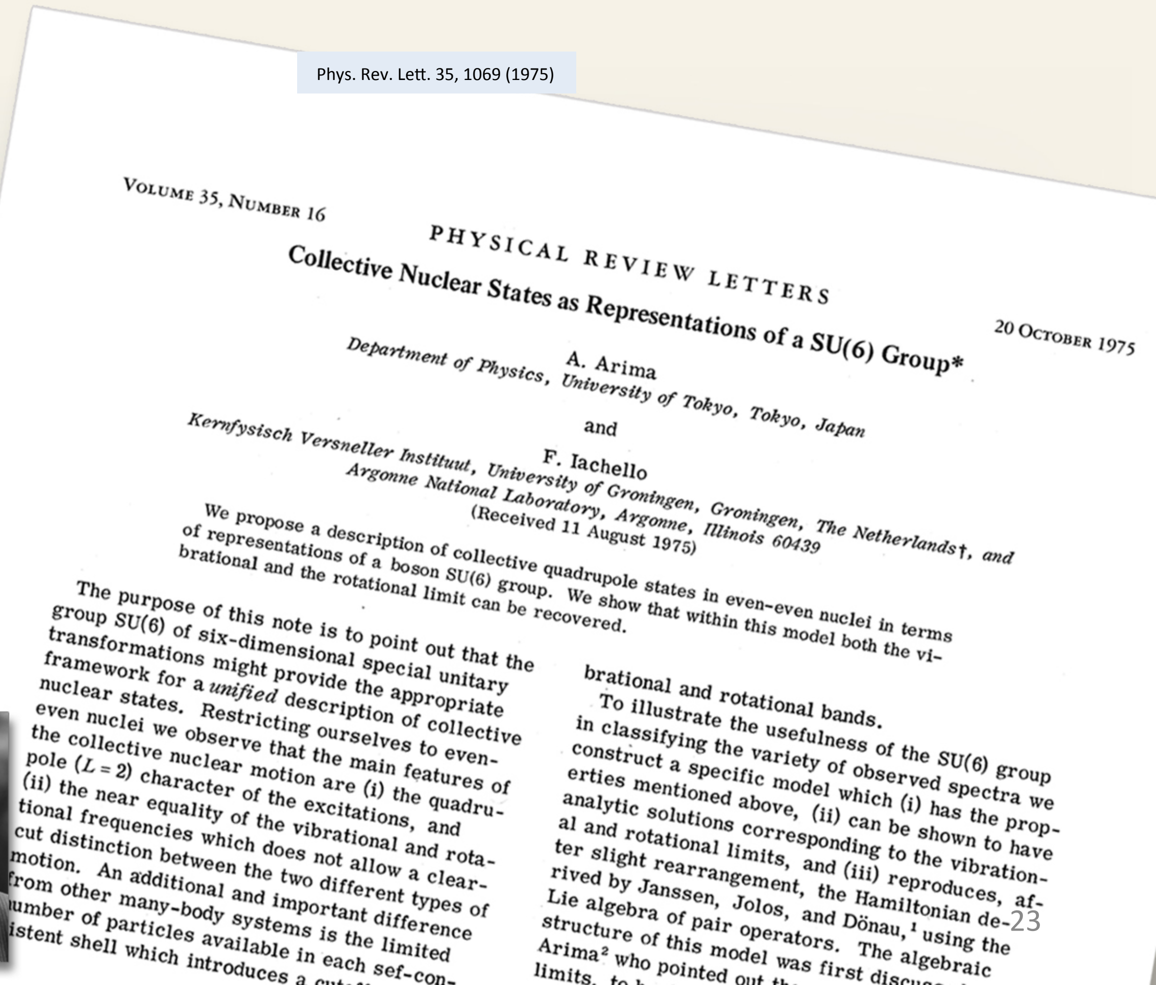
BY

AAGE BOHR AND BEN R. MOTTELSON



1975: **Group-theoretical symmetries,** (not directly tied to geometry)**, also appear remarkably clearly**

Phys. Rev. Lett. 35, 1069 (1975)


VOLUME 35, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1975

Collective Nuclear States as Representations of a SU(6) Group*

A. Arima
Department of Physics, University of Tokyo, Tokyo, Japan

and

F. Iachello
Kernfysisch Versneller Instituut, University of Groningen, Groningen, The Netherlands†*, and Argonne National Laboratory, Argonne, Illinois 60439*
(Received 11 August 1975)

We propose a description of collective quadrupole states in even-even nuclei in terms of representations of a boson SU(6) group. We show that within this model both the vibrational and the rotational limit can be recovered.

The purpose of this note is to point out that the group SU(6) of six-dimensional special unitary transformations might provide the appropriate framework for a *unified* description of collective nuclear states. Restricting ourselves to even-even nuclei we observe that the main features of the collective nuclear motion are (i) the quadrupole ($L = 2$) character of the excitations, and (ii) the near equality of the vibrational and rotational frequencies which does not allow a clear-cut distinction between the two different types of motion. An additional and important difference from other many-body systems is the limited number of particles available in each sef-consistent shell which introduces a

brational and rotational bands.

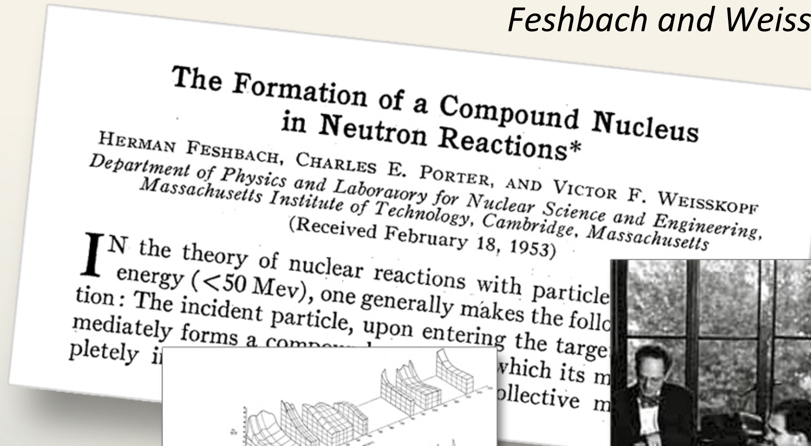
To illustrate the usefulness of the SU(6) group in classifying the variety of observed spectra we construct a specific model which (i) has the properties mentioned above, (ii) can be shown to have analytic solutions corresponding to the vibrational and rotational limits, and (iii) reproduces, after slight rearrangement, the Hamiltonian derived by Janssen, Jolos, and Dönau,[1] using the Lie algebra of pair operators. The algebraic structure of this model was first discussed by Arima[2] who pointed out the

Nuclear Reactions

Need the right tool to learn about the structure of nuclei.

How do reactions proceed?

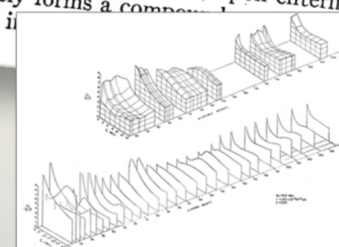
Averaged interaction, and the transparency noted in the shell-model lead to the 'Optical model' of Feshbach and Weisskopf



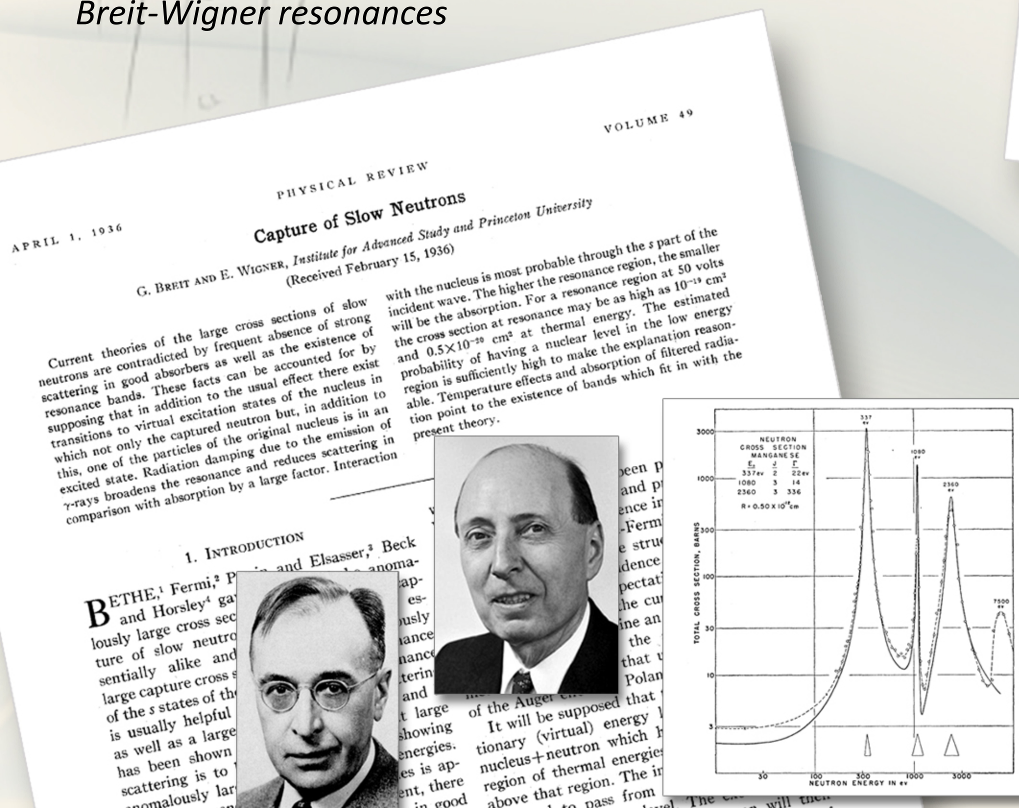
The Formation of a Compound Nucleus in Neutron Reactions*

HERMAN FESHBACH, CHARLES E. PORTER, AND VICTOR F. WEISSKOPF
Department of Physics and Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received February 18, 1953)

IN the theory of nuclear reactions with particle energy (<50 Mev), one generally makes the follo tion: The incident particle, upon entering the targe mediately forms a compo which its m pletely i ollective m



Slowly, through a compound nucleus, with intermediate Breit-Wigner resonances



APRIL 1, 1936 PHYSICAL REVIEW VOLUME 49

Capture of Slow Neutrons

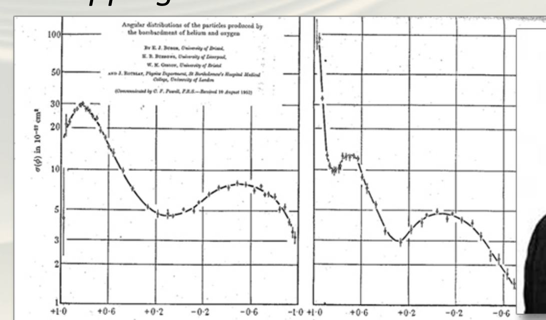
G. BREIT AND E. WIGNER, Institute for Advanced Study and Princeton University
(Received February 15, 1936)

Current theories of the large cross sections of slow neutrons are contradicted by frequent absence of strong scattering in good absorbers as well as the existence of resonance bands. These facts can be accounted for by supposing that in addition to the usual effect there exist transitions to virtual excitation states of the nucleus in which not only the captured neutron but, in addition to this, one of the particles of the original nucleus is in an excited state. Radiation damping due to the emission of γ-rays broadens the resonance and reduces scattering in comparison with absorption by a large factor. Interaction with the nucleus is most probable through the s part of the incident wave. The higher the resonance region, the smaller will be the absorption. For a resonance region at 50 volts the cross section at resonance may be as high as 10^{-19} cm² and 0.5×10^{-20} cm² at thermal energy. The estimated probability of having a nuclear level in the low energy region is sufficiently high to make the explanation reasonable. Temperature effects and absorption of filtered radiation point to the existence of bands which fit in with the present theory.

1. INTRODUCTION

BETHE,[1] Fermi,[2] P and Elsasser,[3] Beck and Horsley[4] ga lously large cross sec ture of slow neutro sentially alike and large capture cross s of the s states of th is usually helpful as well as a large has been shown scattering is to omalously lar

Fast 'stripping' and other direct reactions of Butler

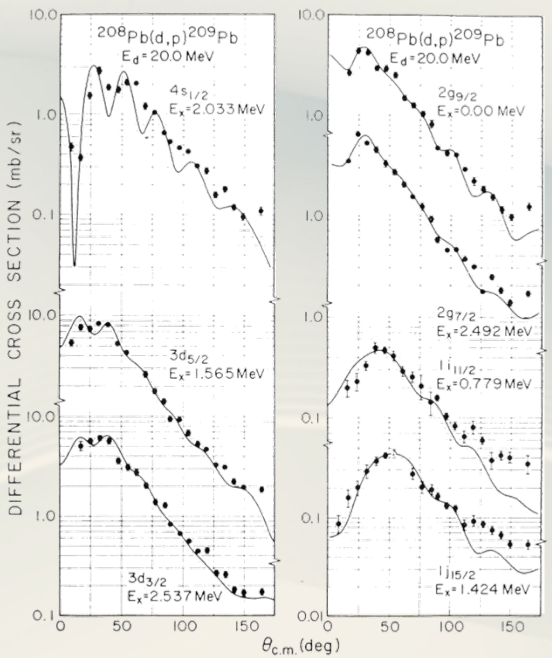


Nucleon transfer

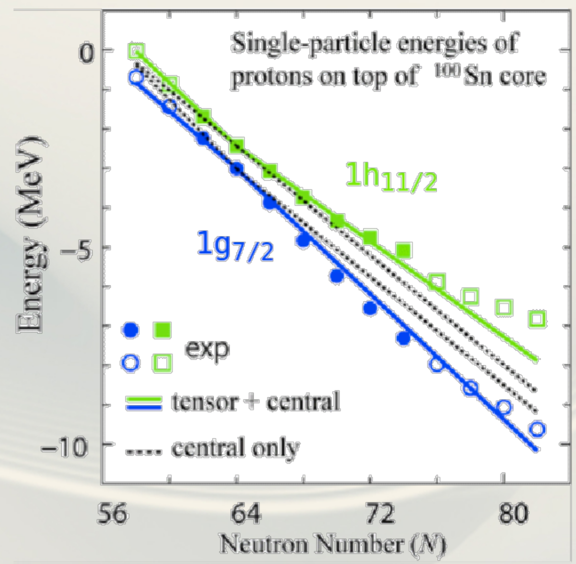
together with *knockout* reactions, are critical in identifying underlying single-particle (hole) states., the skeleton of nuclear structure.

They trace crucial trends, such as the effects of the tensor force.
Similarly, inelastic reactions select collective excitations.

1970-s: Single-neutron states outside ^{208}Pb

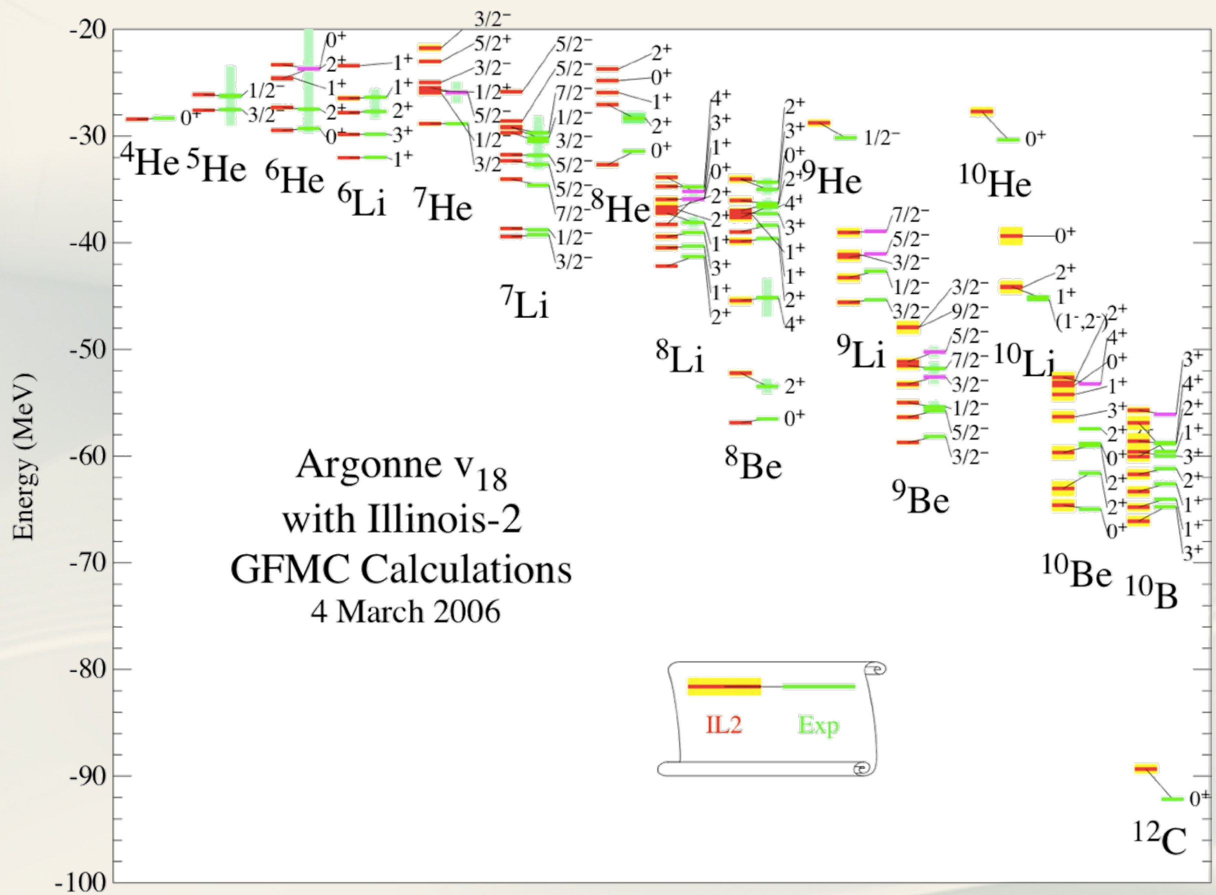


2000-s: Tensor force can change shell structure



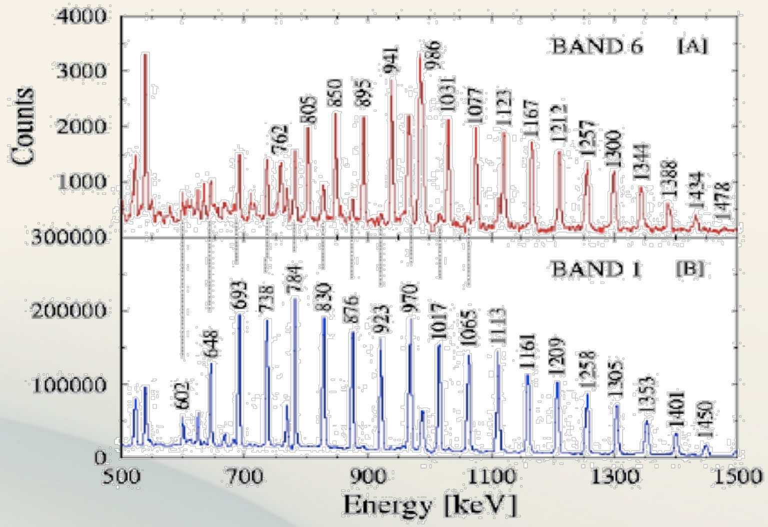
Modern approach:

Can nuclear structure be explained *ab origine*, starting with the NN interaction, and without any model assumptions? *(it takes very large-scale calculations).*



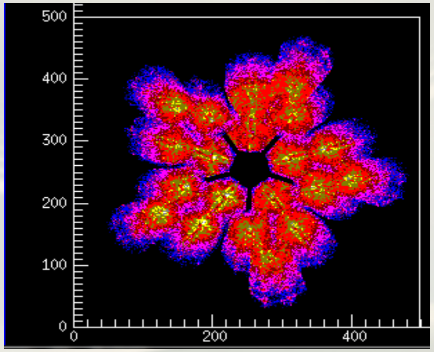
Symmetries shining through

exquisite structure with the powerful techniques of γ-spectroscopy.



^{152}Dy

Gammasphere



First breath of Gretina

Thread:

Applications of nuclear physics

The discovery of fission

Naturwissenschafter 26 163 (1939)

Über die Bruchstücke beim Zerplatzen des Urans

Von Otto Hahn und Fritz Strassmann, Berlin-Dahlem[1].

In unserer letzten Mitteilung[2] über die Entstehung
aktiver Bariumisotope aus Uran und Thorium haben
wir bereits einige Versuche beschrieben, aus denen
f die Entstehung von Edelgas und Alkalimetall
m Zerplatzen des Urans mit Sicherheit geschlossen
len kann. Es konnte beim Schreiben der ge-
ten Arbeit aber noch nicht entschieden werden,
sich dabei um Krypton und Rubidium oder um
und Caesium handelt. Im ersteren Fall wäre
eite Uranbruchstück Barium, im letzteren
n. Aktive Isotope sowohl von Barium
tium hatten wir in dem Uran selbst ja na

schen den beiden Möglichkeiten zu e
r der gegebene Weg die chemische u

Nature 143, 239 (1939)

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

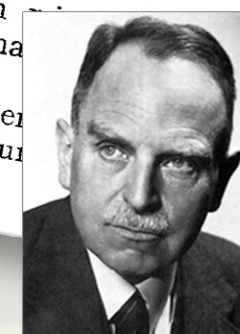
On bombarding uranium with neutrons, Fermi and
collaborators[1] found that at least four radioactive
substances were produced, to two of which atomic
numbers larger than 92 were ascribed. Further
investigations[2] demonstrated the existence of at least
nine radioactive periods, six of which were assigned
elements beyond uranium, and nuclear isomerism
be assumed in order to account for their
al behaviour together with their genetic
ns.

Lise Meitner.

Physical Institute,
Academy of Sciences,
Stockholm.

O. R. Frisch.

itute of Theoretical Physics,
iversity,



The Impact of the Manhattan Project

The Manhattan project impressed on society that physics had something to offer (good or bad).

This success had an enormous impact on the support for all of physics in the second half of the 20th century.

Other Societal Applications

Nuclear energy, another application of fission, showed great promise – but society seems reluctant − perhaps because of the tie to weapons. (*would be interesting to see whether 50-100 years hence this will have changed*).

Nuclear fusion may or may not be a practical source of energy.

Nuclear medicine is enormously successful and used extensively – it somehow has avoided the onus of being 'nuclear'.

Accelerators, developed for nuclear physics, are used widely around the world, estimated at ~10,000 in medicine, 20,000 in industry.

Many applications to other sciences

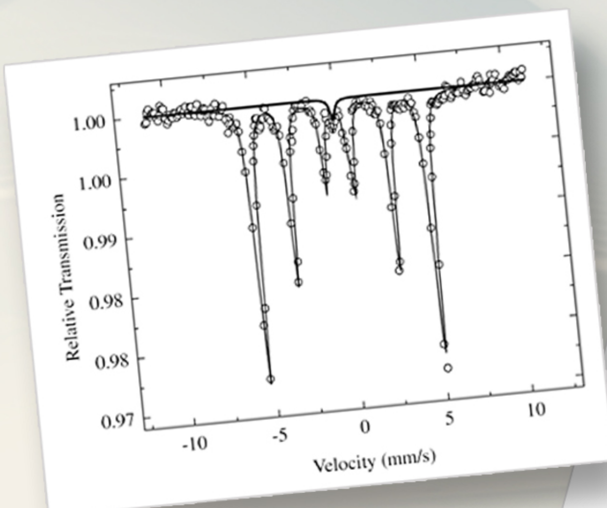
Mössbauer effect (condensed matter, ...)

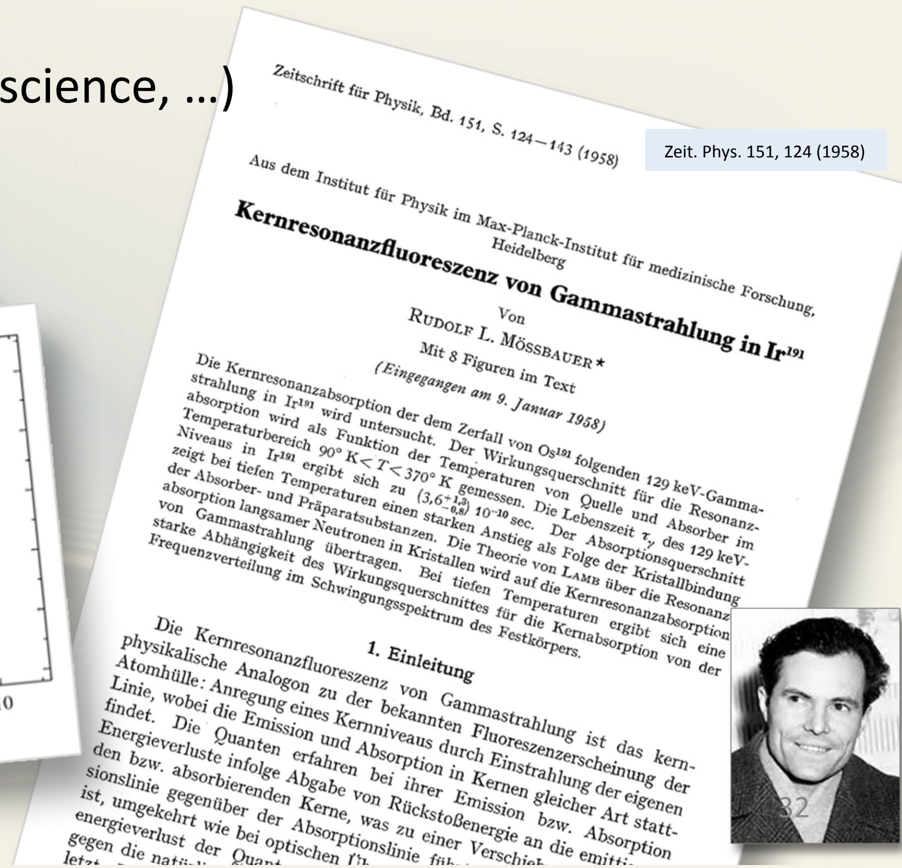
^{14}**C** and other isotopes (archeology, geology, history, oceanography …)

Accelerator Mass Spectrometry, traps, etc. (same as above)

Isotopes in biology, chemistry, …

Rutherford back-scattering (planetary science, …)





Zeitschrift für Physik, Bd. 151, S. 124—143 (1958)

Aus dem Institut für Physik im Max-Planck-Institut für medizinische Forschung, Heidelberg

Kernresonanzfluoreszenz von Gammastrahlung in Ir^{191}

Von

Rudolf L. Mössbauer*

Mit 8 Figuren im Text

(Eingegangen am 9. Januar 1958)

Die Kernresonanzabsorption der dem Zerfall von Os^{191} folgenden 129 keV-Gammastrahlung in Ir^{191} wird untersucht. Der Wirkungsquerschnitt für die Resonanzabsorption wird als Funktion der Temperaturen von Quelle und Absorber im Temperaturbereich 90° K < T < 370° K gemessen. Die Lebenszeit τ_γ des 129 keV-Niveaus in Ir^{191} ergibt sich zu $(3{,}6^{+1{,}3}_{-0{,}8})\,10^{-10}$ sec. Der Absorptionsquerschnitt zeigt bei tiefen Temperaturen einen starken Anstieg als Folge der Kristallbindung der Absorber- und Präparatsubstanzen. Die Theorie von Lamb über die Resonanzabsorption langsamer Neutronen in Kristallen wird auf die Kernresonanzabsorption von Gammastrahlung übertragen. Bei tiefen Temperaturen ergibt sich eine starke Abhängigkeit des Wirkungsquerschnittes für die Kernabsorption von der Frequenzverteilung im Schwingungsspektrum des Festkörpers.

1. Einleitung

Die Kernresonanzfluoreszenz von Gammastrahlung ist das kernphysikalische Analogon zu der bekannten Fluoreszenzerscheinung der Atomhülle: Anregung eines Kernniveaus durch Einstrahlung der eigenen Linie, wobei die Emission und Absorption in Kernen gleicher Art stattfindet. Die Quanten erfahren bei ihrer Emission bzw. Absorption Energieverluste infolge Abgabe von Rückstoßenergie an die emittierenden bzw. absorbierenden Kerne, was zu einer Verschiebung der Emissionslinie gegenüber der Absorptionslinie führt ...

Zeit. Phys. 151, 124 (1958)

Thread:

Neutrinos

a Nuclear Physics Story

How continuous β spectra were explained in 1930

In Rutherford, Chadwick and Ellis

RADIATIONS
FROM
RADIOACTIVE SUBSTANCES

by

SIR ERNEST RUTHERFORD, O.M., D.Sc., Ph.D., LL.D., F.R.S.
NOBEL LAUREATE
Cavendish Professor of Experimental Physics in the University of Cambridge

JAMES CHADWICK, Ph.D., F.R.S.
Fellow of Gonville and Caius College, Cambridge

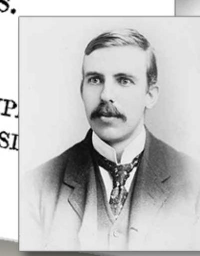
and

C. D. ELLIS, Ph.D., F.R.S.
Fellow of Trinity College, Cambridge

NEW YORK: THE MACMILLAN COMP…
…MBRIDGE, ENGLAND: AT THE UNIVERSI…
1930

We have seen that it is unlikely that the electrons exist in the free state in the nucleus and that many facts suggest that they are bound in pairs to an α particle, forming what has been called an α' particle. The nucleus may thus be considered as built up of α particles, protons, and α' particles, all in definite quantum states. Owing to the large masses of these particles there is no difficulty in associating them with plausible energies but yet keeping their de Broglie wave-lengths of the order of the dimensions of the nucleus.

The usual development of this view is that the β ray changes are initiated by an α particle disintegration involving the departure of the α particle of one of the α' particles. This, however, would again



Genesis of the Neutrino

1930: Pauli suggests light neutral particle to explain β spectra.

1934: Fermi works out β decay with a zero-mass 'neutrino'.

1953: Reines observes neutrinos.

Nuovo Cim. 11, 1 (1934)

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (1) di ENRICO FERMI

Sunto. - *Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del « neutrino » e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegrazione β con un procedimento simile a quello seguito nella teoria dell'i... per descrivere l'emissione di un quanto di luce da un atom... Vengono dedotte delle formule per la vita media e per la f... spettro continuo dei raggi β, e le si confrontano coi dati sp...*

Abschrift/1

Offener Brief an die Grunpe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez.
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich ...ichts der "falschen" Statistik der N- und Li-6 Kerne, sowie ...ntinuierlichen beta-Spektrums auf einen verzweifelten Ausw... ...len um den "Wechselsatz" (1) der Statistik und den Energi... ...ten. Nämlich die Möglichkeit, es könnten elektrisch neutr... ...en, die ich Neutronen nennen will, in den Kernen existier... ...den Spin 1/2 haben und das Ausschliessungsprinzip befolg... ...von Lichtquanten ausserdem noch dadurch unterscheiden, da... ...mit Lichtgeschwindigkeit laufen. Die Masse der Neutrone... ...von derselben Grossenordnung wie die Elektronenmasse s... ...falls nicht grösser als 0,01 Protonenmasse.- Das kontinu... ...Spektrum wäre dann verständlich unter der Annahme, dass ... noch ein Neutron emitt...

Detection of the Free Neutrino*

F. REINES AND C. L. COWAN, JR.
Los Alamos Scientific Laboratory, University of Calif...
Los Alamos, New Mexico

(Received July 9, 1953; revised manuscript received September 14, 1953)

Phys. Rev. 92, 830 (1953)

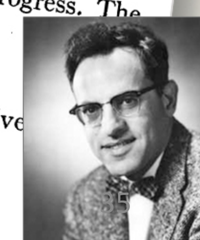
AN experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_- + p \rightarrow n + \beta^+,$$

has been calculated[2,3] from beta-decay theory to be give... expression,

$$\sigma = \left(\frac{G^2}{2\pi}\right)\left(\frac{\hbar}{mc}\right)^2\left(\frac{p}{mc}\right)^2\left(\frac{1}{v/c}\right),$$

where σ = cross section in barns; p, m, v = momentum, mass... velocity of emitted positron (cgs units)... (cm/sec); $2\pi\hbar$ = Planck...



Neutrinos

Does Dirac's theory of the electron apply to neutrinos? Or are the rules different when there is no charge?

Proc. Roy. Soc. A 117 610 (1928)

The Quantum Theory of the Electron.

By P. A. M. DIRAC, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received January 2, 1928.)

The new quantum mechanics, when applied to the problem of the structure … the atom with point-charge electrons, does not give results in agreement … with experiment. The discrepancies consist of " duplexity " phenomena, the … observed number of stationary states for an electron in an atom being twice the number given by the theory. To meet the difficulty, Goudsmit and Uhlen- … have introduced the idea of an electron with a spin angular momentum … and a magnetic moment of one Bohr magneton. This model … as been fitted into the new mechanics by Pauli,* and Darwin,† … equivalent theory, has shown that it gives results in agreement … for hydrogen-like spectra to the first order of accuracy. … remains as to why Nature should have chosen this particular … electron instead of being satisfied with the point-charge. One … find some incompleteness in the previous methods of applying … mechanics to the point-charge electron such that, when removed, … duplexity phenomena follow without arbitrary assumptions. … the case, the incompleteness of … with relativity, or, alternate- … mechanics. It

Nuovo Cim. 14 171 (1937)

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* DIRAC *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

…'interpretazione dei cosidetti « stati … da DIRAC (1) conduce, come è ben n… …mente simmetrica degli elettroni e … …metria del formalismo consiste pre… …è possibile applicare la teoria gira… …ssa fornisce realmente risultati de… …tifici suggeriti per dare alla teoria … con il suo contenuto, non sono … parte sempre da una impostaz… …etrizzazione viene in seguito … …ome la cancellazione di costan… …ero evitarsi. Perciò abbiamo te… …irettamente alla meta. …arda gli elettroni e i positroni … soltanto un …

Fotografia di Ettore Majorana tratta dalla tessera universitaria datata 3 novembre 1923

Neutrinos

The Weak Interaction

1956: Lee & Yang suggest parity is not conserved in β decay.

1957: Wu, Ambler, Hayward et al. show that indeed it is not.

1958: Goldhaber et al. show that neutrinos have left-handed chirality.

Phys. Rev. 105 1671 (1957)

PHYSICAL REVIEW VOLUME 105, NUMBER 5 MARCH 1, 1957

Parity Nonconservation and a Two-Component Theory of the Neutrino

T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang, *Institute for Advanced Study, Princeton, New Jersey*

(Received January 10, 1957; revised manuscript received January 17, 1957)

A two-component theory of the neutrino is discussed. The theory is possible only if parity is not conserved in interactions involving the neutrino. Various experimental implications are analyzed. Some general remarks concerning nonconservation are made.

Recently the question has been raised[1,2] as to whether the weak interactions are invariant under space inversion, charge conjugation, and time reversal. It was pointed out that although these invariances are generally held to be valid for all interactions, experimental proof has so far only extended to cover the strong interactions. (We group here the electromagnetic interactions with the strong interactions.) To test the possible violation of these invariance laws in the weak interactions, a number of experiments were proposed. One of these is to study the angular distribution of the β ray coming from the decay of oriented nuclei. ...

is mathematically equivalent to a familiar four-component neutrino formalism for which all parity-conserving and parity-nonconserving Fermi couplings C and C' (as defined in the appendix of reference 1) are always related in the following manner: $C_S=C_S'$, $C_V=C_V'$, etc. or $C_S=-C_S'$, $C_V=-C_V'$, etc. Sections 3 to 8 are devoted to the physical consequences of the theory that can be put to experimental test. In the last section some general remarks about nonconservation are made.

I. NEUTRINO FIELD

1. Consider first the Dirac equation for a free spin-$\frac{1}{2}$ particle with zero mass. Because of the absence of the mass term, one needs only three anticommuting Hermitian matrices. Thus the neutrino can be represented by a spinor function φ_ν which has only two components.[4] The Dirac equation for φ_ν can be written as ($\hbar=c=1$)

$$\boldsymbol{\sigma}\cdot\mathbf{p}\varphi_\nu=i\partial\varphi_\nu/\partial t, \quad (1)$$

where $\sigma_1, \sigma_2, \sigma_3$ are the usual 2×2 Pauli matrices. The relativistic invariance of this equation for proper Lorentz transformations (i.e., Lorentz transformations without space inversion and time inversion) is well known. In particular, for the space rotations through an angle θ around, say, the z axis, the wave function transforms in the following way:

$$\varphi\rightarrow\exp(-i\sigma_3\theta/2)\phi. \quad (2)$$

Phys. Rev. 105 1413 (1957)

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

In a recent paper[1] on the question of parity in interactions, Lee and Yang critically surveyed experimental information concerning this question reached the conclusion that there is no existing evide either to support or to refute parity conservation in w interactions. They proposed a number of experiments beta decays and hyperon and meson decays which wou provide the necessary evidence for parity conservatio or nonconservation. In beta decay, one could measure the angul ... beta deca ... distributi ... between ... momentu ... unequivo ... decay. T ... case of o ...

It has ... be polar ... magnesi ... zation ... succeed ... present ...

Phys. Rev. 109, 1015 (1958)

Helicity of Neutrinos*

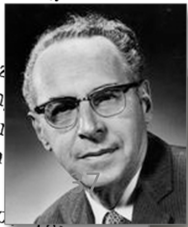
M. Goldhaber, L. Grodzins, and A. W. Sunyar

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A combined analysis of circular polariz resonant scattering of γ rays followin electron capture measures the helicity of the We have carried out such a measurement with which decays by orbital electron capture. If we the most plausible spin-parity assignment fo isomer compatible with its decay scheme,[1] 0−, ... that the neutrino is "left-handed," ... (negative helicity).

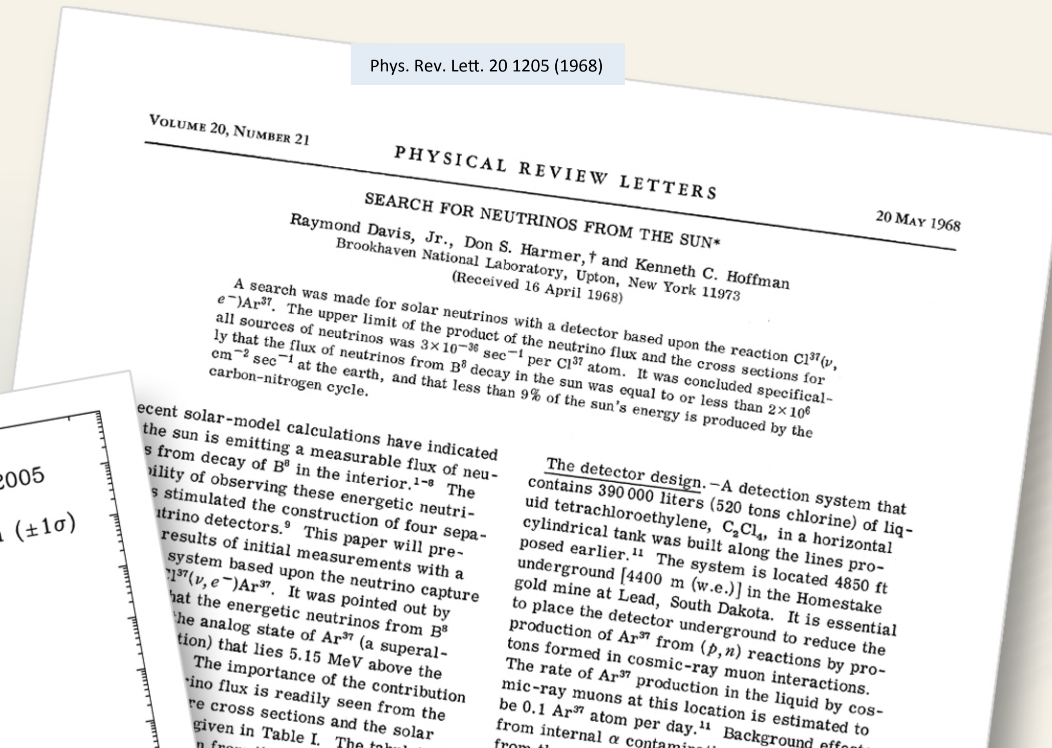
Our method ... simple ...



Neutrinos

Looking for solar neutrino

Davis finds substantially fewer neutrinos, than ***Bahcall*** expected from his calculations.



Phys. Rev. Lett. 20 1205 (1968)

VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

SEARCH FOR NEUTRINOS FROM THE SUN*

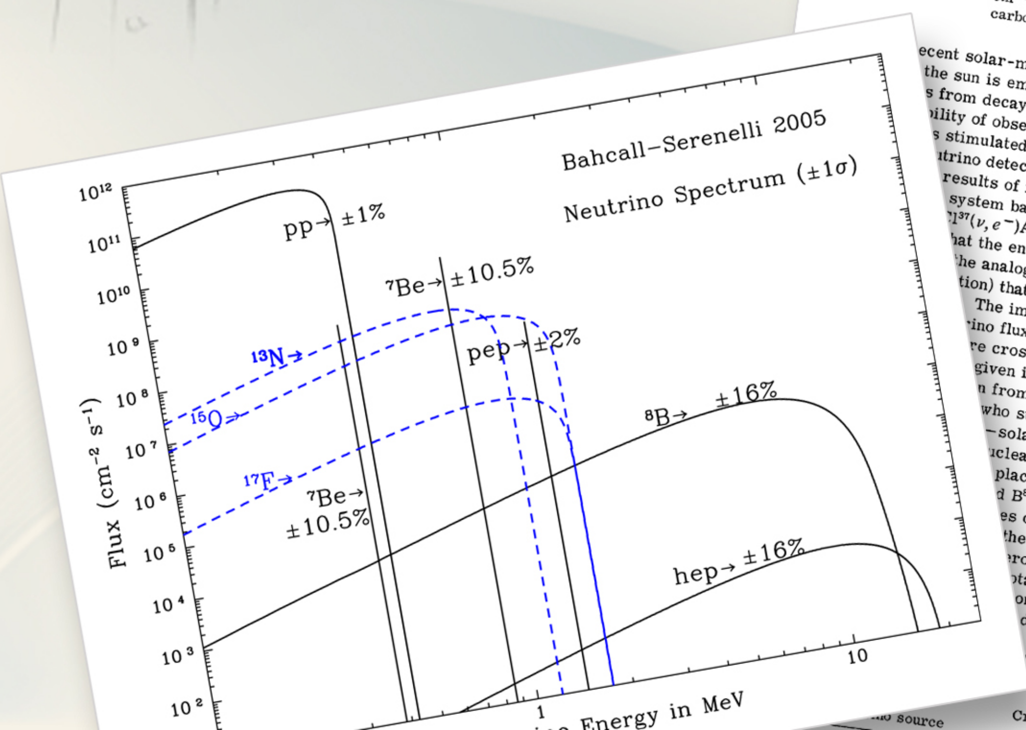
Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973

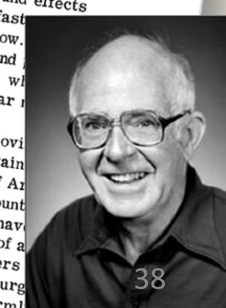
(Received 16 April 1968)

A search was made for solar neutrinos with a detector based upon the reaction $Cl^{37}(\nu, e^-)Ar^{37}$. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was 3×10^{-36} sec^{-1} per Cl^{37} atom. It was concluded specifically that the flux of neutrinos from B^8 decay in the sun was equal to or less than 2×10^6 cm^{-2} sec^{-1} at the earth, and that less than 9% of the sun's energy is produced by the carbon-nitrogen cycle.

…ecent solar-model calculations have indicated the sun is emitting a measurable flux of neu…s from decay of B^8 in the interior.[1-8] The …ility of observing these energetic neutri…s stimulated the construction of four sepa…trino detectors.[9] This paper will pre… results of initial measurements with a system based upon the neutrino capture …$l^{37}(\nu, e^-)Ar^{37}$. It was pointed out by …hat the energetic neutrinos from B^8 …he analog state of Ar^{37} (a superal…tion) that lies 5.15 MeV above the … The importance of the contribution …ino flux is readily seen from the …re cross sections and the solar …given in Table I. The tabulated …n from the calculations of Bah… who studied the effect of errors …—solar composition, luminos…uclear reaction cross sections. …placed a probable error of …d B^8 flux. Their predicted …es of the various parame… the independent calcula…ron.[5] On the basis of …tal solar-neutrino-cap…ons of chlorine would be … day.

The detector design.—A detection system that contains 390 000 liters (520 tons chlorine) of liquid tetrachloroethylene, C_2Cl_4, in a horizontal cylindrical tank was built along the lines proposed earlier.[11] The system is located 4850 ft underground [4400 m (w.e.)] in the Homestake gold mine at Lead, South Dakota. It is essential to place the detector underground to reduce the production of Ar^{37} from (p,n) reactions by protons formed in cosmic-ray muon interactions. The rate of Ar^{37} production in the liquid by cosmic-ray muons at this location is estimated to be 0.1 Ar^{37} atom per day.[11] Background effects from internal α contaminations and fast …

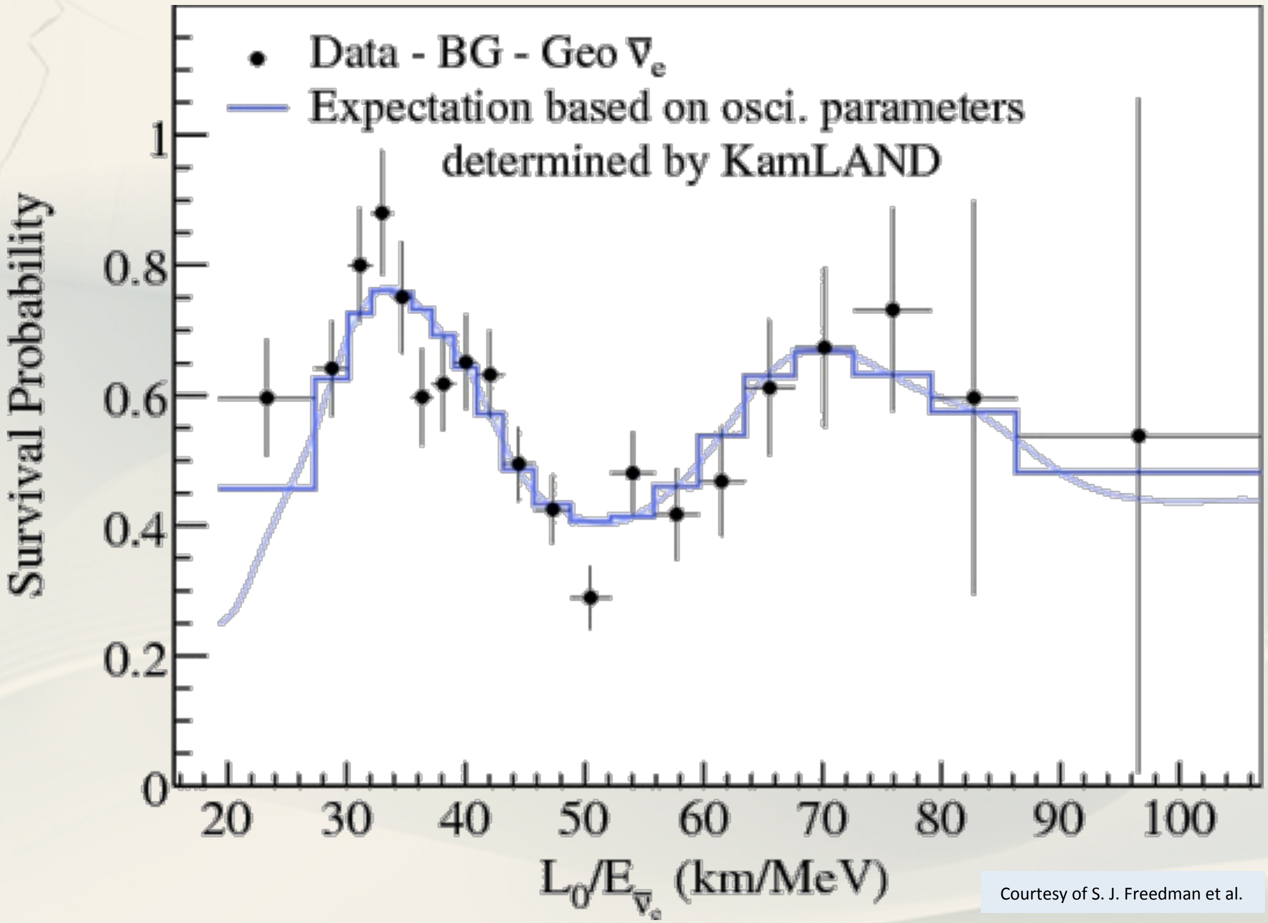




Neutrino oscillations

By now, these have been mapped out in terrestrial measurements.

Neutrinos have finite-mass (differences)!



Courtesy of S. J. Freedman et al.

But what are the rules for neutrinos?

Once neutrinos have mass, chirality is not an intrinsic property.

This tends to favor Majorana's idea of 70+ years ago, and it becomes more plausible that a massive, neutral neutrino might be its own anti-particle.

> ***I****s this 'beyond the Standard Model' or not?*
> *The Standard Model, after all, is a model, constrained by what assumptions are fed into it.*

The only test on the horizon is the *nuclear* process of

> ***neutrinoless double beta decay***.

Perhaps the next decade will resolve this fascinating issue?

Origin of elements, fuel of stars

What Fuels the Sun?

Nuclear fusion!

Where do all the elements come from?

Nuclear Reactions!

Rev. Mod. Phys. 29, 547 (1957)


REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4 — OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions"; (*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves (*Julius Caesar*, Act I, Scene

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Phys. Zeit. 38, 176 (1937)


Über Elementumwandlungen im Innern der Sterne. I.

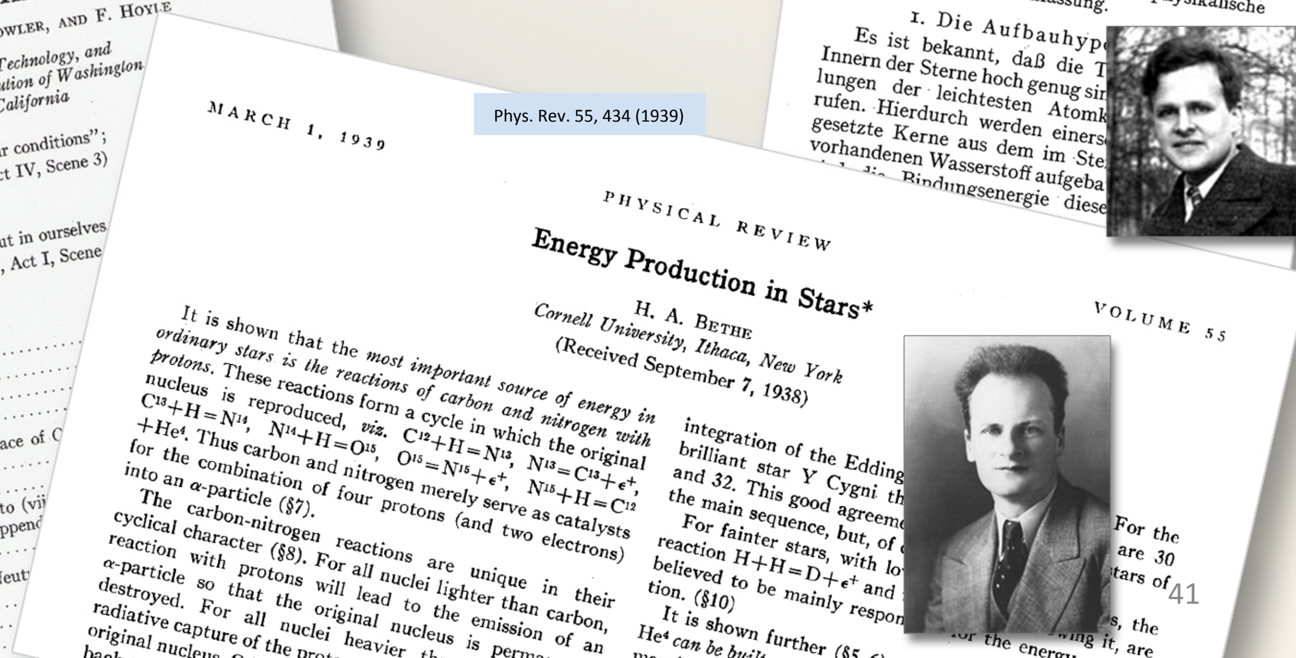
Von C. F. v. Weizsäcker.

1. Die Aufbauhypothese. — 2. Umwandlung durch geladene Kerne. — 3. Reaktionsketten der leichtesten Elemente. — 4. Folgerungen für den inneren Aufbau der Sterne. — 5. Umwandlung durch Neutronen. — 6. Der Aufbau der schwereren Elemente. — 7. Allgemeinere astrophysikalische Fragen. — 8. Zusammenfassung.

1. Die Aufbauhyp

Es ist bekannt, daß die T
Innern der Sterne hoch genug sin
lungen der leichtesten Atomk
rufen. Hierdurch werden einers
gesetzte Kerne aus dem im Ste
vorhandenen Wasserstoff aufgeba
Bindungsenergie diese

Phys. Rev. 55, 434 (1939)


MARCH 1, 1939 — PHYSICAL REVIEW — VOLUME 55

Energy Production in Stars*

H. A. BETHE

Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier th radiative capture of the prot original nucleus

integration of the Edding brilliant star Y Cygni th and 32. This good agreem the main sequence, but, of

For fainter stars, with lo reaction $H+H=D+\epsilon^+$ and believed to be mainly respon tion. (§10)

It is shown further He⁴ can be buil

For the are 30 tars of

s, the ing it, are or the energy

Threads

New forms of matter

Fascination with things that may (or may not) exist

New forms of matter

New elements, the dream of alchemists

Fermi's prize-winning mistake *(Ausenium and Hesperium)* followed by ~25 real transuranic elements.

105 … 118 Dubna

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

P7 - 3808

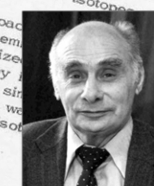
Dubna Rep. P7-3808 (1968)

Препринт Объединенного института ядерных исследований. Дубна, 1968.

Flerov G.N., Druin V.A., Demin A.G., Lobanov Yu.V., Skobelev N.K., Akapiev G.N., Fefilov B.V., Kolesov I.V., Gavrilov K.A., Kharitonov Yu.P., Chelnokov L.P.

Experiments on Search for α-Radioactive Isotopes of Element 105

Preprint. Joint Institute for Nuclear Research. Dubna, 1968



Nature 133 898 (1934)

Possible Production of Elements of Atomic Number Higher than 92

By Prof. E. Fermi, Royal University of Rome

UNTIL recently it was generally admitted that an atom resulting from artificial disintegration should normally correspond to a stable isotope. M. and Mme. Joliot first found evidence that it is not necessarily so; in some cases the product atom may be radioactive with a measurable mean life, and go over to a stable form only after emission of a positron.

94 … Berkeley

Phys. Rev. 69 366 (1946)

Radioactive Element 94 from Deuterons on Uranium

G. T. Seaborg, E. M. McMillan, J. W. Kennedy, and A. C. Wahl

Department of Chemistry, Radiation Laboratory, Department of Physics, University of California, Berkeley, California

January 28, 1941*

WE are writing to report some results obtained in the bombardment of uranium with deuterons in the 60-inch cyclotron.

107 … GSI

Zeitschrift für Physik A Atoms and Nuclei © Springer-Verlag 1981

Short Note

Identification of Element 107 by α Correlation Chains

G. Münzenberg, S. Hofmann, F.P. Heßberger, W. Reisdorf, K.H. Schmidt, J.H.R. Schneider, and P. Armbruster

Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Federal Republic of Germany

C.C. Sahm

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B. Thuma

II. Physikalisches Institut, Universität Gießen, D-6300 Gießen, Federal Republic of Germany

Z. Phys. A 300 107 (1983

113 … RIKEN

Journal of the Physical Society of Japan Vol. 73, No. 10, October, 2004, pp. 2593–25 ©2004 The Physical Society of Japan

Experiment on the Synthesis of Element 113 in the Reaction $^{209}Bi(^{70}Zn,n)^{278}113$

Kosuke Morita, Kouji Morimoto, Daiya Kaji, Takahiro Akiyama, Sin-ichi Goto, Hiromitsu Haba, Eiji Ideguchi, Rituparna Kanungo, Kenji Katori, Hiroyuki Koura, Hisaaki Kudo, Tetsuya Ohnishi, Akira Ozawa, Toshimi Suda, Keisuke Sueki, HuShan Xu, Takayuki Yamaguchi, Akira Yoneda, Atsushi Yoshida and YuLiang Zhao

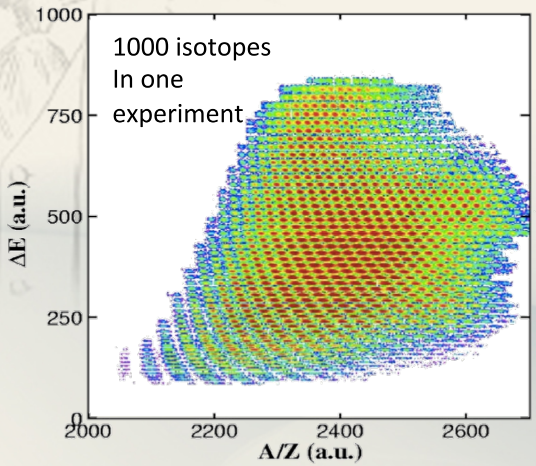
(Received July 30, 2004)

J. Phys. Soc. Jap 73, 2593 (2004)

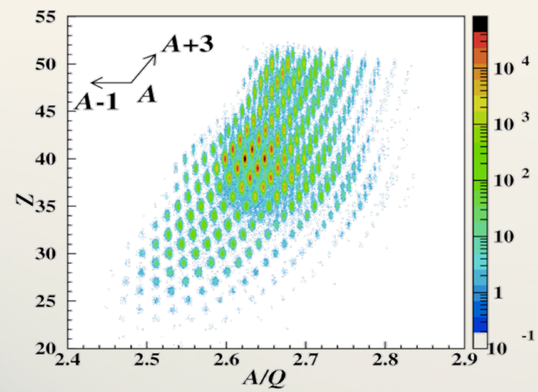
New isotopes

All particle-stable nuclei seem to be made in fragmentation.

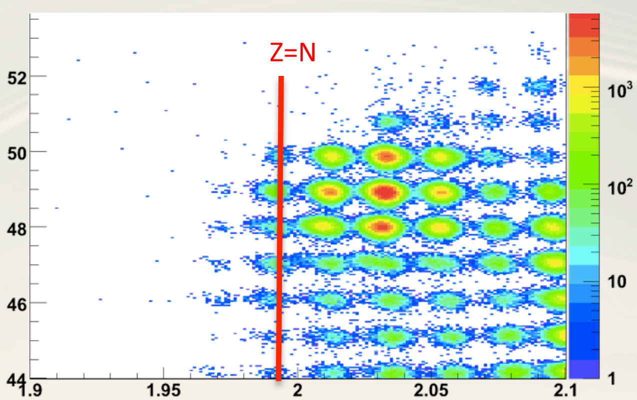
What are their properties?

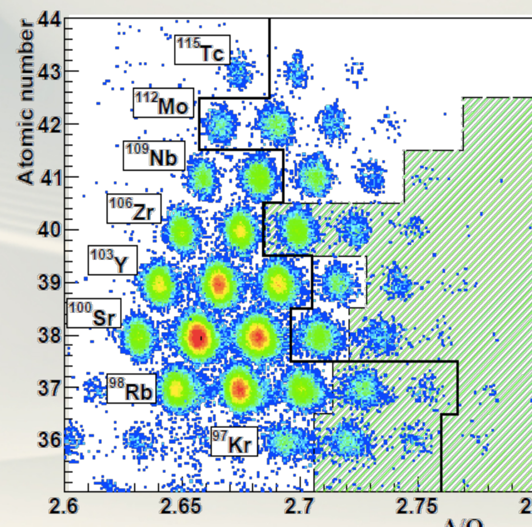


At RIKEN (neutron-rich around Z≈40)



At GSI (proton rich, around ^{100}Sn)



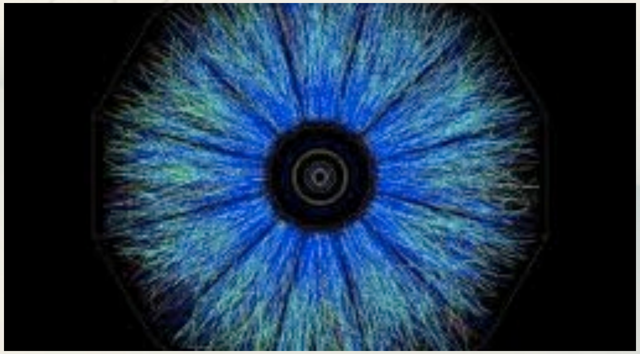


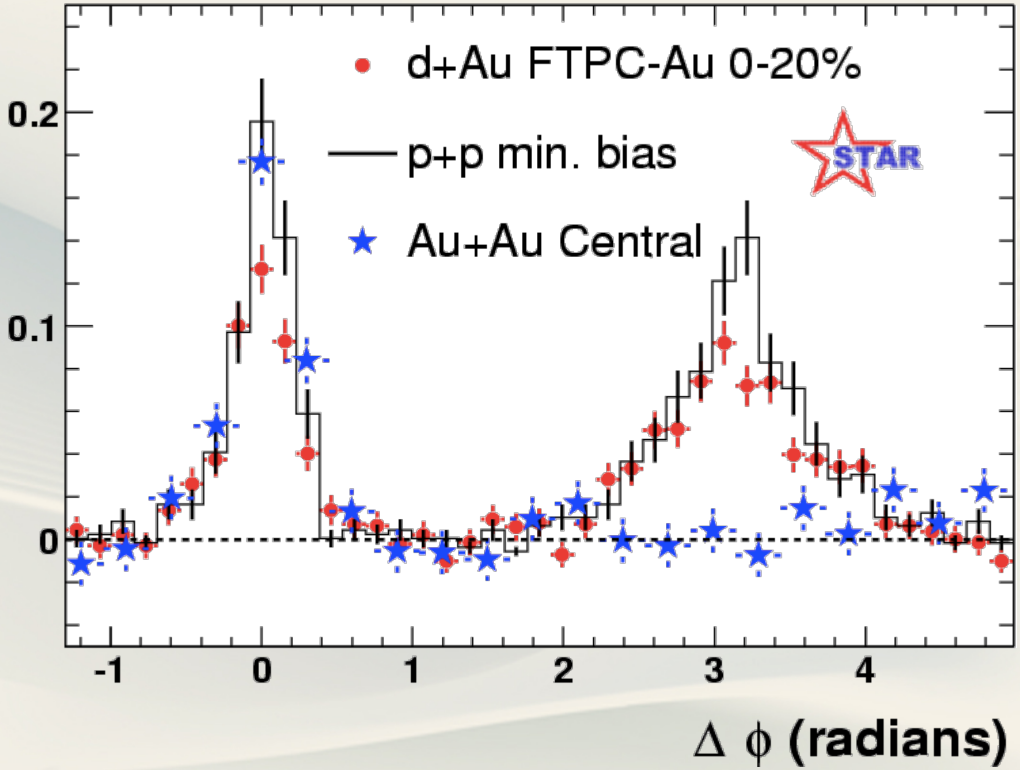
Exploration of the limits of energy density.

Out of the complexity of collisions, signatures of a deconfined **Quark-Gluon Plasma** are evident, for instance in the opacity to 2-jet events.

(Behavior consistent with weakly coupled plasma – connection to string theory?)

Adams *et al.*, Phys. Rev. Let. 91 (2003)072304





Reflections

The world concentrates the visible matter of which we are made almost entirely into nucleons, that are then cooked in stars into nuclei.

Some see nuclear physics as mired down in messy effects that get in the way of the essential simplicities of nature.

Nuclear physicists try to understand why and how our world is the way it is, why quarks and gluons appear ***only*** as these 'messy' hadrons, how these hadrons form nuclei that then show beautiful simplicities.

Perhaps what seems 'messy' and what is ‘fundamental’ is a reflection of the limitations of our understanding.

Hadrons

It is amusing that high-energy physics split off from nuclear physics ~50 years ago to study the properties of hadrons. **H**adrons turned out to have structure, thus not 'elementary' and were returned to nuclear physics.

Electrons determine most properties of atoms, yet they contain only ~0.1 % of the mass. Their binding lowers the mass.

Quarks determine most properties of protons and hadrons, yet they contain only ~1% of the mass: their binding *(their intrinsic confinement)* dominates the mass.

We are just beginning to gain some possible insights into the question:

Why is the mass and structure of hadrons what it is?

’Elementary’ particles, their nature and masses

The ***Standard Model*** has been very successful but we still have no understanding of the very specific numbers: masses, mixing angles, etc. that describe the elementary particles.

Higher and higher energies will perhaps shed light on these issues, but nuclear physics has contributed much – on neutrinos and on other issues -- and this is likely to continue.

Why do we have the specific masses and mixing matrices for quarks and leptons?

Are neutrinos Majorana's neutrinos: are they their own antiparticles?

Nuclei

Our world consists overwhelmingly of nuclei whose 'messy' complexity conceals some beautiful symmetries – we see these, but our understanding is still incomplete.

The way nuclei are made in the universe in hot stars follows paths through short-lived nuclei, near the limits of stability.

Short-lived nuclei are difficult to make and study in the laboratory – investigations are just beginning.

How do the symmetries in nuclei emerge?

What are the properties of exotic short-lived nuclei at the limits of binding?

How do these properties influence the formation of elements?

Nuclear Physics in the U.K.

Rutherford started Nuclear Physics here at Manchester.

The U.K. provided a fertile intellectual and institutional environment that lead the field in a glorious start for much of its first half century.

In recent decades, the UK funding seems not to have fared as well as other similar countries around the world.

Why?

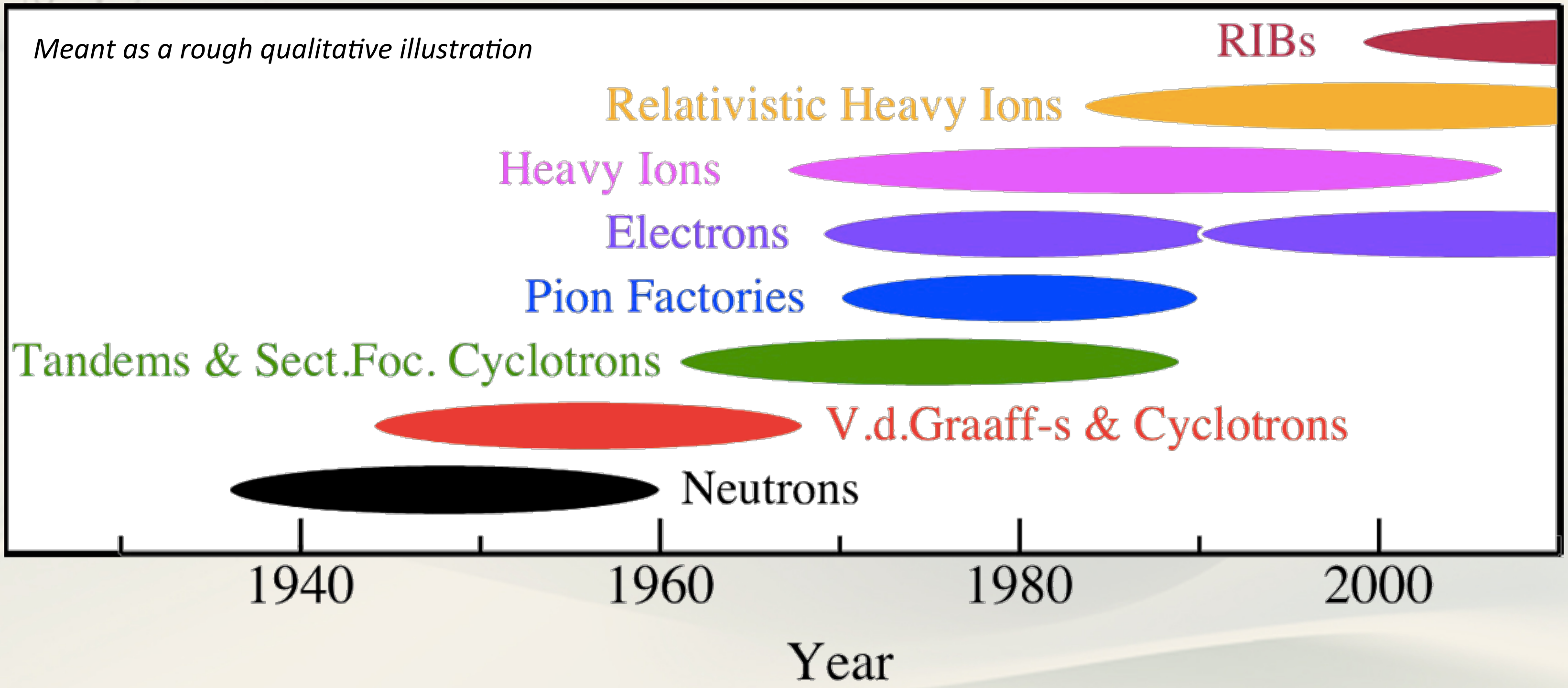
No simple answer: the quality of UK scientists in our field is still very strong *(albeit without any UK facilities)* and they are an important component of the global effort.

Fashions

There are fashions in physics, as in other fields of human activities.

We all want to work on the same questions as our colleagues.

These questions are not necessarily settled before they go out of fashion.



Conclusions I.

Rutherford's discovery of 100 years ago had very broad impact. It opened a window on the nucleus, with all the marvelous interactions, symmetries and rules that manifest themselves in 'nuclear' phenomena.

Nuclear matter accounts for most of the visible, accessible mass in our experience; its interactions produce the energy that makes life possible.
We must continue the quest to better understand the rules that govern our world.

Applications of nuclear physics have had major impacts in medicine, on many aspects of society, and on other sciences. *Even nuclear weapons have helped shape the history of the latter part of the 20th century and (arguably) may have forced governments to be realistic, and reject another major war as a viable option.*

Conclusions II.

Our species has an insatiable curiosity that has served it very well in the evolutionary process.

Science, enabled by relatively stable societies, is a modern manifestation of this very basic human trait.

We, practicing scientists in the last 100-200 years, are privileged to be participating in unique advances in human knowledge and understanding.

We hope it will continue -- if only our species can also learn to use its intellect to control some of its other evolutionary drives. Stable rational civilizations are essential to enable science, the human quest for knowledge and understanding, to continue and flourish.

??!   … but, but, *we* are ‘nuclear’
… and so was Rutherford !??

… but, I guess with the fine print, Rutherford and we can still feel welcome.

It says:
'DEDICATED TO ALL THOSE WHO STRIVE FOR PEACE AND TO RID THE WORLD OF NUCLEAR WEAPONS'